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THE METALLURGY OF IRON AND STEEL

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THE METALLURGY OF IRON AND STEEL

BY

BRADLEY STOUGHTON, PH. B., B. S.

SECOND EDITION, THOROUGHLY REVISED AND ENTIRELY RESET

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TO

PROFESSOR HENRY MARION HOWE, A.M., LL.D.,

BESSEMER MEDALLIST, KNIGHT OF THE ORDER OF

ST. STANISLAS, ETC., ETC.,

PRACTITIONER, INVESTIGATOR, AUTHOR, INTERPRETER,

EDUCATOR AND PHILOSOPHER, WHOM THE WORLD

OF SCIENCE DELIGHTS TO HONOR,

THIS VOLUME IS

AFFECTIONATELY DEDICATED

PREFACE TO SECOND EDITION

Developments in the Metallurgy of Iron and Steel have been so rapid during the past three years that a more thorough revision of the text of this volume than could be accomplished in conjunction with the usual reprinting for new impressions seemed not only desirable but necessary. Every department of manufacture has been improved in practice, in minor respects at least, and some branches, such as the duplex and special open-hearth processes, electric smelting and refining, use of dry blast, case-hardening, etc., have been advanced sufficiently to warrant an entire rewriting of the sections devoted to them. Opportunity has been taken of these revisions to make more or less extensive changes in all the text, with the result that it has been necessary to reset the type from cover to cover. I am especially indebted to J. E. Johnson, Esq., for valuable suggestions and revisions of the chapters on blast furnace, and chemistry and physics.

In addition to the changes mentioned above, the theory and chemistry of the Bessemer and open-hearth processes have been rewritten and enlarged, as well as the whole chapter on malleable cast iron. The section on blast furnace fuels has been taken from Chapter II, and this also has been rewritten and enlarged; with the section on open-hearth fuels from Chapter VI, it has been embodied in a new Chapter XIX, on Metallurgical Fuels. The references to literature have, in accordance with several suggestions, been taken from the end of the individual chapters and collected in an Appendix at the end of the volume, thus rendering it easier to turn to the index numbers at will.

In making these changes a constant and serious handicap has been the necessity of keeping the number of pages within a small compass in order not to disturb the price at which the book is sold, especially for the sake of student purses.

It will be noticed that the numbering of the illustrations is not quite consecutive, but a few numbers are left out at the

end of most of the chapters. The purpose of this arrangement is to allow additional cuts to be inserted from time to time if desired, without waiting until a third edition becomes necessary—if it ever does.

BRADLEY STOUGHTON.

NEW YORK CITY,
October 16, 1911.

PREFACE TO FIRST EDITION

The purpose of this book is to serve as a text-book, not only for college work, but for civil, mechanical, electrical, metallurgical, mining engineers and architects, and for those engaged in work allied to engineering or metallurgy. America now produces almost as much iron and steel as the rest of the world together, although less than eighteen years ago she held second rank in this industry. It seems fitting that the record of this progress should be brought together into one volume covering every branch of the art of extracting the metal from its ores and of altering its adaptable and ever-varying nature to serve the many requirements of civilized life.

I take pleasure in acknowledging here, with sincere thanks the assistance of many who have aided in the make-up of the volume, and especially The Adams Co., American Electric Furnace Co., American Sheet & Tinplate Co., Bethlehem Steel Co., Brown Specialty Machinery Co., Connersville Blower Co., Crocker-Wheeler Co., Francis G. Hall, Esq., Holland Linseed Oil Co., Chas. W. Hunt, Esq., Secretary, American Society of Civil Engineers, Professor James F. Kemp, Mackintosh, Hemphill & Co., Morgan Construction Co., National Tube Co., S. Obermayer Co., J. W. Paxson Co., Henry E. Pridmore, John A. Rathbone, each of whom have kindly loaned electrotypes. And of Dr. H. C. Boynton, the Brown Hoisting Machinery Co., Buffalo Furnace Works, H. H. Campbell, Esq., Professor William Campbell, Carnegie Steel Co., W. M. Carr, Esq., Central Iron & Steel Co., Crucible Steel Company of America, Fiske & Robinson, The Foundry, Harbison-Walker Refractories Co., Joseph Hartshorne, Esq., Professor Henry M. Howe, Lackawanna Steel Co., Marion Steam Shovel Co., Mesta Machine Co., Morgan Engineering Co. , Professor A. H. Sexton, Wm. Swindell & Bros., United Coke & Gas Co., United Engineering & Foundry Co., Wellman-Seaver-Morgan Co., Whiting Foundry Equipment Co. And of O. S. Doolittle, Esq., for information upon paint, Frank E. Hall, Esq., for the analyses in Table XVIII, and W. J. Keep, Esq., for the figures in Table XXVI.

But especially I am indebted to the following gentlemen, each of whom has read a section of the book and made suggestions for its revision which have been very valuable to me: Messrs. W. Arthur Bostwick, Stanley G. Flagg, Jr., Alfred E. Hammer, Joseph Hartshorne, J. E. Johnson, Jr., Carleton S. Kock Frank N. Speller, Herbert L. Sutton, and Hugh P. Tiemann.

BRADLEY STOUGHTON.

September 1, 1911.

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THE METALLURGY OF IRON AND STEEL

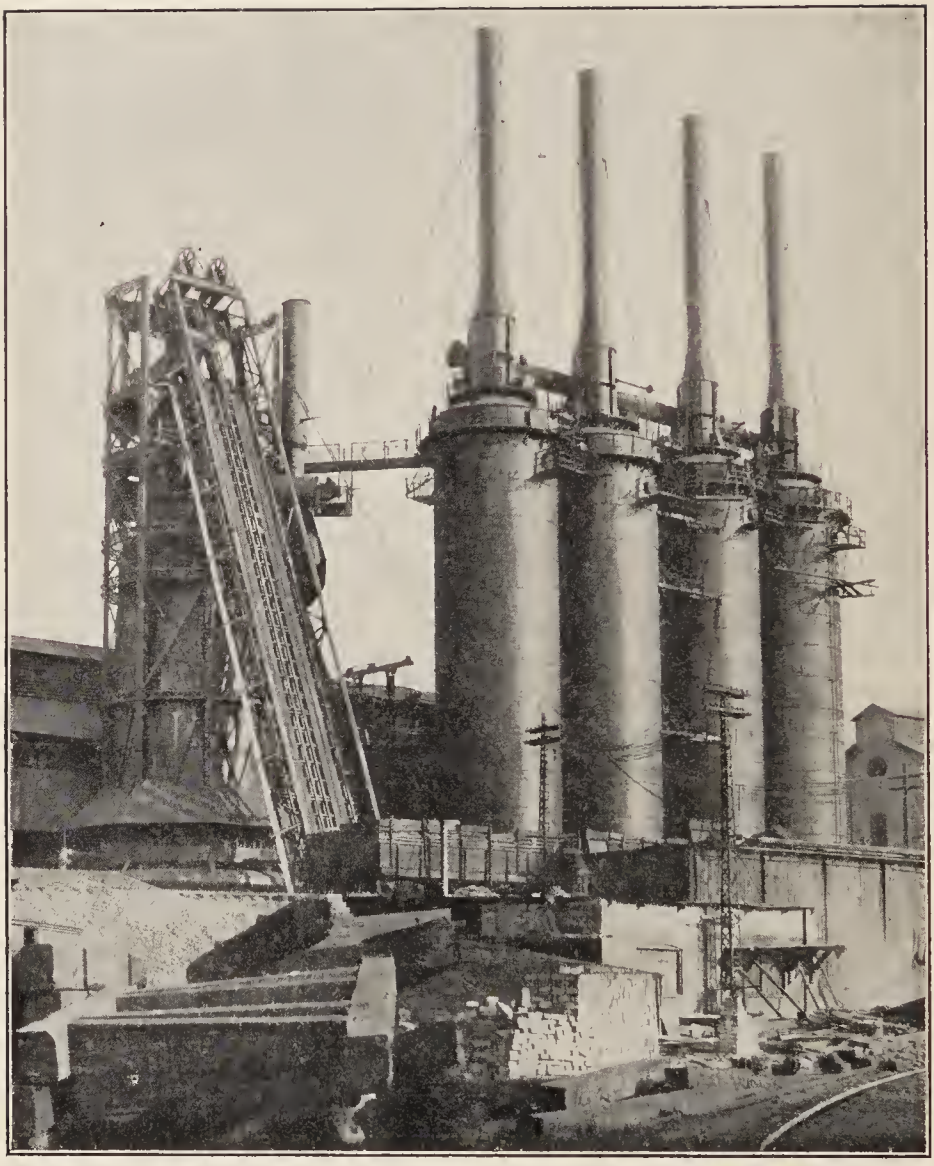


FIG. I.—IRON BLAST FURNACE AND STOVES.

I

INTRODUCTION—IRON AND CARBON

This chapter is written for those students of iron and steel—whether they be students engaged at some university, or in an engineering or metallurgical profession—who have previously completed a course in chemistry and physics. For the benefit of those who have not had a technical education, Chapter XX has been especially prepared, and it is hoped that, if they will read that chapter before beginning elsewhere in the book, all the subjects discussed in these pages will be readily intelligible to them.

The Ferrous Metals.—Iron and steel together form the largest manufactured product in the world, and each of them enters into every branch of industry and is a necessary factor in every phase of our modern civilization. Cast iron, because of the ease with which it can be melted, is produced in final form in almost every city in the United States, and only slightly less widely in other civilized countries. The manufacture of steel is more centralized, for economical reasons, but is several times as great as that of cast iron. Wrought iron is less in amount than either of the others, but has its own importance and uses. These three products—cast iron, steel, and wrought iron—together comprise the whole of the so-called "ferrous group of metals"—that is, the group which we classify together under the name of "iron and steel." They have two characteristics in common: First, that iron is present in all to the extent of at least 92 per cent.; and second, that carbon is their next most important ingredient, and regulates and controls their chief qualities. Their manufacture represents nearly 15 per cent. of all the world's manufacturing wealth, and is far greater than any other like industry. (See Table I.)

Cast Iron.—Cast iron is impure, weak, and must be brought to its desired size and form by melting and casting in a mold. A typical example would contain about 94 per cent. iron, 4 per cent. carbon, and 2 per cent. of other ingredients or impurities.

Pig iron is a raw form of cast iron, and malleable cast iron is a semipurified form.

Steel.—Steel is purer than cast iron, much stronger, and may be produced in the desired size and form either by melting and casting in a mold or by forging at a red heat. It usually contains about 98 per cent. or more of iron, and, in different samples, from 1.50 per cent. down to almost no carbon, together with small amounts of other ingredients or impurities.

Wrought Iron.—Wrought iron is almost the same as the very low-carbon steels, except that it is never produced by melting and casting in a mold, but is always forged to the desired size and form. It usually contains less than 0.12 per cent. of carbon. Its chief distinction from the low-carbon steels is that it is made by a process which finishes it in a pasty, instead of in a liquid form, and leaves about 1 or 2 per cent. of slag mechanically disseminated through it.

Iron.—Iron as such—by which I mean pure iron—does not exist as an article of commerce, but appears in service and in the market only in the form of cast iron, steel or wrought iron—that is, when contaminated with carbon and other impurities. Some of these impurities are present because they cannot cheaply be gotten rid of, and others, because, like carbon for example, they benefit the metal by giving it strength or some other desirable property. Pure iron is a white metal and one of the chemical elements. It is with one exception the commonest and most abundant metal in the earth, and almost all rocks contain it in greater or less degree, from which we extract it if it is large enough in amount to pay for working. It is almost never found in nature in the form of a metal, but is always united with oxygen to form either a blackish, brownish, reddish or yellowish substance. Indeed, if it should occur in metallic form it would very soon become oxidized by the action of air and moisture.

It is the abundance of iron in the earth which is the chief cause of its cheapness, and therefore one reason why it is used more than any other manufactured material. The other reason is the ease with which we can confer upon it at will some of the qualities most useful to man, of which the most valuable is probably its strength, and the most wonderful its magnetism, in which it is not even approached by any other substance. What these two properties alone mean in modern structural and electrical engineering can scarcely be estimated.

TABLE I.—THE WORLD'S PRODUCTION OF PIG IRON IN METRIC TONS (22,046 POUNDS), 1865 TO 1910.

	United States	Great Britain	Germany	France	Belgium	Russia	Austria-Hungary	Sweden	Spain	Italy	Canada	Other Countries	Total
1865..	843,410	4,897,971	988,191	1,203,710	470,767	299,438	101,403	226,619	.....	.....	.....	68,037	9,099,666
1870..	1,692,378	6,060,720	1,391,123	1,178,113	565,234	*359,531	402,953	300,338	.....	.....	.....	309,520	12,259,910
1875..	2,056,750	6,469,219	2,029,389	1,448,272	541,805	427,187	463,063	350,539	In 1876 44,491	.....	.....	316,078	14,102,222
1880..	3,897,840	7,875,545	2,792,038	1,725,293	608,084	448,596	464,234	405,713	85,939	.....	.....	306,946	18,547,228
1885..	4,110,600	7,368,842	3,687,434	1,630,648	712,876	528,170	714,787	464,737	159,225	15,991	.....	398,583	19,791,893
1886..	5,776,168	7,124,012	3,528,658	1,516,574	701,677	532,744	719,980	442,457	57,728	12,291	*20,138	*350,000	25,862,289
1887..	6,521,973	6,682,738	4,023,953	1,567,622	755,781	613,184	704,530	456,625	288,634	12,265	22,529	*350,000	22,977,305
1888..	6,595,735	8,129,047	4,337,121	1,683,349	826,850	667,737	790,227	457,052	252,116	12,538	19,781	264,136	24,015,908
1889..	7,871,590	8,458,486	4,524,558	1,734,000	832,226	740,957	855,813	420,665	197,874	13,473	23,522	380,418	26,029,981
1890..	9,353,020	8,033,052	4,658,451	1,962,196	787,836	927,581	965,382	456,103	170,782	14,346	.....	301,959	27,630,712
1891..	8,413,176	7,525,301	4,631,218	1,897,387	684,126	1,004,745	921,846	490,913	278,462	11,930	21,697	*350,000	26,230,081
1892..	9,304,428	6,817,274	4,937,461	2,057,300	753,268	*919,614	940,284	485,664	247,329	12,729	38,514	*350,000	26,863,865
1893..	7,239,806	7,089,318	4,986,030	2,003,100	745,264	1,160,737	982,707	453,421	260,450	8,038	50,750	*350,000	24,229,025
1894..	6,757,248	7,364,745	5,559,322	2,077,647	810,940	1,312,760	1,054,520	459,132	260,000	10,329	*45,327	*350,000	26,058,970
1895..	9,597,449	8,022,006	5,788,798	2,005,889	829,135	1,454,298	1,075,000	455,200	206,430	*10,500	47,586	*375,000	29,867,591
1896..	8,761,197	8,700,220	6,360,982	2,333,702	932,780	1,629,810	1,130,000	466,400	246,326	11,280	47,635	*395,000	31,015,302
1897..	9,807,123	8,930,086	6,888,087	2,472,143	1,024,666	1,857,000	1,205,000	533,800	282,171	12,500	49,497	*450,000	33,513,073
1898..	11,962,317	8,819,968	7,407,717	2,525,075	982,748	2,228,850	1,250,000	492,700	261,799	12,850	69,248	*545,000	36,658,272
1899..	13,838,634	9,572,178	7,160,203	2,578,400	1,036,185	2,708,749	1,323,999	467,727	266,385	19,218	95,582	*625,000	39,722,560
1900..	14,009,870	9,003,046	7,549,655	2,714,298	1,161,180	2,895,636	1,311,949	526,868	289,788	23,990	87,612	*625,000	40,198,892
1901..	16,132,408	7,977,459	7,785,887	2,388,823	765,420	2,807,972	1,300,000	528,375	294,118	25,000	248,896	*635,000	40,889,358
1902..	18,003,448	8,653,976	8,402,660	2,427,427	1,102,910	2,597,435	1,335,000	524,400	330,747	24,500	325,076	*615,000	44,342,579
1903..	18,297,400	8,952,183	10,085,634	2,827,668	1,299,211	2,486,610	1,355,000	506,825	380,284	28,250	269,665	*625,000	47,113,730
1904..	16,760,986	8,699,661	10,103,941	2,999,787	1,307,399	2,978,325	1,369,500	528,525	386,000	27,600	274,777	*633,000	46 069,501
1905..	23,340.258	9,746,221	10 987,623	3.077,000	1,310,290	2,125,000	1,372,300	531,200	383,100	31,300	475,491	*655,000	54,054,783
1906..	25,712,106	10,210,178	12,478,067	3,319,032	1,431,160	2,350,000	1,403,500	552,250	387,500	30,450	550,618	*650,000	59,074.861
1907..	26,193,863	10,082,638	13,045,760	3,588,949	1,427,940	2,768,220	1,405,000	603,100	385,000	32,000	590,444	*556,900	60,680,014
1908..	16,190,994	9,438,477	11,813,511	3,391,150	1,206,440	2,748,000	1,650,000	563,300	403,500	112,924	572,123	*550,000	48,640,479
1909..	26,108,199	9,818,916	12,917,653	3,632,105	1,632,350	2,871,232	1,958,786	443,000	389,000	207,800	687,923	*550,000	61,217,064
1910..	27,636,687	10,380,212	14,794,649	4,032,459	1,803,500	2,740,000	2,010,000	604,300	367,000	215,000	752,053	*525,000	65,860,260

* Estimated.

Carbon.—Carbon is also a chemical element and familiar to everyone; graphite, lamp-black, charcoal, and diamond are the various allotropic forms in which it appears. It is a common substance and present in every form of organic matter, while its oxides—carbon monoxide, CO; and carbon dioxide, CO_2—are well known gases. Its chemical affinity for iron is very great; iron practically always contains some amount, but if it is desired to remove it entirely, the last traces are eliminated only with extreme difficulty.

Iron and Carbon.—Carbon has the peculiarity of conferring on iron great strength, which, strange to say, it does not itself possess, and also hardness, which it possesses only in its diamond allotropic form. At the same time it takes away from the iron a part of its ductility, malleability, magnetism and electric conductivity. So important is the influence of carbon in regulating and controlling the characteristics of the ferrous metals, that they are individually and collectively classified according to the amount and condition of the carbon in them. The potent effect of carbon must be constantly borne in mind when we come to describe the manufacture of iron and steel and to discuss the methods of regulating the carbon.

Definitions

The following definitions are selected from the report of March 31, 1906, of the Committee on the Uniform Nomenclature of Iron and Steel of the International Association for Testing Materials, with slight changes:

Cast Iron.—Generically, iron containing so much carbon or its equivalent that it is not malleable at any temperature. Specifically, cast iron in the form of castings other than pigs, or remelted cast iron suitable for casting into such castings, as distinguished from pig iron, i.e., cast iron in pigs.

The committee recommends drawing the line between cast iron and steel at 2.20 per cent. carbon for the reason that this appears from the results of Carpenter and Keeling to be the critical percentage of carbon corresponding to the point "a" in the diagrams of Roberts-Austen and Roozeboom. (See page 295).

Pig Iron.—Cast iron which has been cast into pigs direct from the blast furnace. This name is also applied to molten cast iron which is about to be so cast into pigs, or is in a condition

in which it could readily be cast into pigs before it has ever been cast into any other form.

Gray Pig Iron and Gray Cast Iron.—Pig iron and cast iron in the fracture of which the iron itself is nearly or quite concealed by graphite, so that the fracture has the gray color of graphite.

White Pig Iron and White Cast Iron.—Pig iron and cast iron in the fracture of which little or no graphite is visible, so that their fracture is silvery and white.

Mottled Pig Iron and Mottled Cast Iron.—Pig iron and cast iron, the structure of which is mottled, with white parts in which no graphite is seen, and gray parts in which graphite is seen.

Malleable Cast Iron.—Iron which when first made is cast in the condition of cast iron, and is made malleable by subsequent treatment without fusion.

Malleable Iron.—The same as wrought iron. A name used in Great Britain, but not in the United States, except carelessly as meaning "Malleable cast iron."

Steel.—Iron which is malleable at least in some one range of temperature, and in addition is either (*a*) cast into an initially malleable mass; or (*b*) is capable of hardening greatly by sudden cooling; or (*c*) is both so cast and so capable of hardening.

Wrought Iron.—Slag-bearing, malleable iron, which does not harden materially when suddenly cooled.

In the definition of steel the first sentence ("is malleable at least in some one range of temperature") distinguishes steel from cast iron and pig iron; the second sentence ("is cast into an initially malleable mass") distinguishes it from malleable cast iron, and the third sentence ("is capable of hardening greatly by sudden cooling") distinguishes it from wrought iron. At the best, however, the definition of steel is in a shockingly bad condition, and has been brought to it by a series of events which shows the carelessness of the buying public and the greed of men who will appropriate the name for their product that will bring them the best price without regard to whether the name really fits or not.[1]

[1] See page 173 of reference No. 1, and page 6 of No. 2. Especially see H. M. Howe, Eng. and Min. Jour., Feb. 11, 1911, Vol. 91, pp. 327–330.

II

THE MANUFACTURE OF PIG IRON

WHATEVER material we are to manufacture—cast iron, wrought iron, or steel—or for whatever purpose the metal is to be used, the first step in the operation is smelting iron ore in a blast furnace with fuel and flux, and obtaining cast iron or pig iron, terms used synonymously in the United States. The pig iron thus produced is an impure grade of iron, containing chiefly carbon, silicon, manganese, sulphur and phosphorus. The amount of pig iron made exceeds that of any other product manufactured by man. Blast furnace fuels, are discussed in Chapter XIX.

ANALYSIS OF VARIOUS GRADES OF PIG IRON.

NAME	Silicon Per cent.	Sulphur Per cent.	Phosphorus Per cent.	Manganese Per cent.	Carbon Per cent.
Foundry Irons.[1] No. 1...	2.75	0.035	0.30 to 1.50	0.20 to 1.60	3.00 to 4 00
Foundry Irons.[1] No. 2...	2.25	0.045	0.30 to 1.50	0.20 to 1.60	3.00 to 4.00
Foundry Irons.[1] No. 3...	1.75	0.055	0.30 to 1.50	0.20 to 1.60	3.00 to 4.00
Foundry Irons.[1] No. 4...	1.25	0.065	0.30 to 1.50	0.20 to 1.60	3.00 to 4.00
Forge Iron[2].....	0.75 to 1.75	0.05 to 0.30	0.30 to 3.00	0.20 to 1.50	3.00 to 4.00
Bessemer—Acid.....	0.80 to 2.00	0.03 to 0.08	under 0.10	0.30 to 0.50	3.50 to 4.00
Bessemer—Basic....	under 1.00	under 0.10	1.75 to 3.50	1.00 to 2.00	3.50 to 4.00
Open-hearth—Acid...	0.75 to 2.50	under 0.050	under 0.05	0.30 to 0.50	3.50 to 4.00
Open-hearth—Basic.	under 1.00	under 0.100	0.10 to 2.00	1.00 to 2.00	3.50 to 4.00
Ferromanganese[3]. ..	0.50 to 1.00	under 0.03	0.10 to 1.00	80.00	5.00 to 7.00
Ferromanganese[3]....	under 1.00	under 0.03	0.10 to 0.50	40.00	5.00 to 6.00
Spiegeleisen[3].....	under 1.00	under 0.05	under 0.15	15.00 to 30.00	5.00 to 6.00
Ferrosilicon[4].....	8.00 to 15.00	under 0.07	0.10 to 0.50	.....	1.00 to 2.00
Ferrosilicon[5].....	50.00	under 0.02	under 0.08	.....	under 0.40
Silico-Spiegel[6].....	8.00 to 15.00	under 0.01	under 0.15	15.00 to 20.00	1.00 to 1.50
Ferro-Chrome[7].....	1.00 to 5.00	about 0.04	0.02 to 0.05	.....	5.50 to 10.0
Ferro-Chrome[8].....	Low.....	about 0.04	0.02	.....	under 1.0

[1] See also Chapter IX.
[2] Used for Puddling. See Chapter IV.
[3] Valued for its manganete.
[4] Valued for its silicon
[5] This grade is made by electric smelting.
[6] Valued for its maganese and silicon.
[7] Valued for its chromium which is about 60 to 70 per cent.
[8] Special low carbon.

The gangue of our iron ores consists usually of silica, alumina, etc., and, like the fuel ash, requires the addition of the correct amount of limestone flux to make it into a fusible slag. In the Pittsburg district we charge about 1200 lb. of limestone, 2200 lb. of coke, and 4000 lb. of ore for every long ton of pig iron made. The amount of each is increasing, however, from time to time, as the higher-grade ores are becoming exhausted and there are more impurities to be fluxed and melted. Recently, enriching ores by wet concentration has been practised more extensively, and "washers" at or near the mines decrease the proportion of useless impurities to be transported and to be treated in the furnace, while magnetic concentrators are important in the eastern United States.

Varieties and Distribution of Iron Ores

The iron ores used for smelting consist of chemical compounds of iron and oxygen containing more or less water, either in the form of moisture or chemically combined as water of crystallization.

Hematite (Fe_2O_3).—The best known of these ores is hematite, containing when pure 70 per cent. of iron. The red or brown hematites are the richer varieties (Lake Superior deposits, containing, in some cases, as much as 68 per cent. of iron), while the hydrated hematites, or limonites, usually contain a good deal of water of crystallization and are consequently poorer in iron, not often yielding much more than 50 per cent. iron.

Oölitic hematite is a variety that exists in the form of spherical grains or nodules. It is important because it sometimes contains limestone and is, therefore, valuable not only for the iron but for the fluxing quality of the lime. The Minette ore of Lothringen (formerly Lorraine), Luxemburg, and France is an enormous deposit of this oölitic hematite, running from 30 to 35 per cent. iron and giving a pig iron containing about 2 per cent. of phosphorus. This ore is the basis of the iron industry of Germany, France, and Belgium, and, upon judicious mixing of varieties when necessary, is self-fluxing.

Magnetite (Fe_3O_4).—Magnetite contains, when pure, enough iron (72.4 per cent.) to attract the magnet. In the United States it is often mixed with other impurities, such as silica, titanium, and phosphorus, so as to render the ore either too poor in iron to be

smelted profitably, or too high in phosphorus to make good steel, or so high in titanium as to unjustly[1] prejudice smelters against it through fear of sticky, infusible slags.

But other magnetite ores—notably those of Sweden—are the purest ores that exist in large quantities anywhere, and form one of the sources of the Swedish iron and steel, which is famous all over the world for its purity, that is, for its freedom from the objectionable elements sulphur and phosphorus. It is these Swedish products which supply the steel industry of Sheffield with pure material for its tool steel and cutlery.

Siderite ($FeCO_3$).—Another variety of iron ore is the so-called "spathic" iron ore, or siderite, which is, however, without any importance in the United States. This forms the famous "clay ironstone" of the Cleveland district in England. It is poor in iron and is therefore no longer smelted in any quantity in the United States in competition with the rich hematites. This ore is almost always calcined before smelting to expell the carbonic acid, in order to save the blast furnace the extra work of this expulsion in its upper levels.

SUMMARY OF IRON ORE DEPOSITS OF UNITED STATES.

(Compiled by James F. Kemp.)[a]

	Available metric tons	Probable addition metric tons
Archean magnetites (Appalachian)	.....	.....
Lump ores	20,000,000	30,000,000
Concentrate equivalent from low-grade ore	40,000,000	10,000,000
Adirondack red hematites	2,000,000	2,000,000
Pennsylvania soft magnetites	40,000,000	.....
Cambro-ordovician brown hematites (Appalachian)	65,000,000	181,000,000
Mesozoic and tertiary brown hematites (Ala., Tenn.)	10,000,000	15,000,000
Alabama gray and red hematites	27,500,000	27,500,000
Clinton red hematites (largely Ala., Tenn., N. Y. and Wis.)	505,320,000	1,368,000,000
Carbonate ores (Ohio, Penn., and Ky.)	.....	308,000,000
Lake Superior hematites (Minn., Mich., Wis.)	3,500,000,000	72,000,000,000
Mississippi valley specular and red hematites (Mo.)	15,000,000	5,000,000
Mississippi valley paleozoic brown hematites (Mo.)	30,000,000	45,000,000
Mississippi valley tertiary brown hematites (La., Tex., Ark.)	260,000,000	520,000,000
Cordilleran magnetites and hematites (Utah, Cal., Wyo., Nev., Colo.)	63,800,000	55,000,000
Total	4,578,620,000	74,566,500,000
Titaniferous ores (Adirondacks and Lake Superior)	90,000,000	128,500,000

(a) "Iron Ore Resources of the World," Stockholm, 1910.

[1] See Jour. Ir. and St. Inst., No. 1, 1910, pp. 611–2.

WORLD'S SUMMARY OF IRON ORE RESERVES. (a)
(In million metric tons.)

	Actual reserves		Potential reserves	
	Ore	Iron	Ore	Iron
Europe	12,032	4,733	41,029+	12,029+
America	9,855	5,154	81,822+	40,731+
Australia	136	74	69+	37+
Asia	260	156	457+	283+
Africa	125	75	much	much
Total	22,408	10,192	123,337+	53,136+

(a) "Iron Ore Resources of the World," Stockholm, 1910.

United States Deposits and Transportation

In the United States ores of iron are very widely distributed, as will be seen by reference to the map below. The smelting

FIG. 2.—FROM KEMP'S "ORE DEPOSITS OF THE UNITED STATES."

of ore also shows a wide distribution. Blast furnaces are in operation in twenty-four states, including Washington, Minne-

sota, and New York on the north; California, Texas, and Alabama on the west and south. The great pig-iron centers are: (1) The district that includes Western Pennsylvania and Ohio, which produces more than one-half of the pig iron of the country; (2) Illinois, and (3) Alabama.

It is not to be supposed that all the deposits marked on the map are extensively worked for their iron. The rich hematite deposits of the Lake Superior district furnish annually about 40,000,000 tons, which yield more than three-quarters of the pig-iron production of the country. The only other districts which produce more than 1,000,000 tons a year are in the states of Alabama and New York. Most of the other deposits are mined only for local treatment. In addition, a total of over 2,000,000 tons per year are imported from Cuba, Spain, and other foreign countries, principally for smelting on or near the Atlantic coast, while Pacific coast furnaces receive ores from China.

Ore Transportation.—A peculiarity of the Lake Superior deposits is that most of the ore is transported a distance of 800 miles or more in order to bring it to the coke. Thus, Western Pennsylvania, Ohio and South Chicago receive the bulk of the

FIG. 3.—A LAKE SUPERIOR ORE MINE.

ore shipped from the Lake Superior mines. Since the weight of coke used in the blast furnaces is only about one-half the weight of the ore, it might seem uneconomical to carry the latter to the former. But coke is bulky in proportion to its weight; furthermore, it suffers a good deal of waste in transportation in consequence of its friability and of the fact that so much of it is broken down into pieces less than an inch in diameter (technically known as "breeze") which is not suitable for charging into the blast furnace. The ore, on the other hand, may be handled by the cheapest and most rapid labor-saving devices. Indeed, in many cases, the ore is never touched by shovels in the hands of

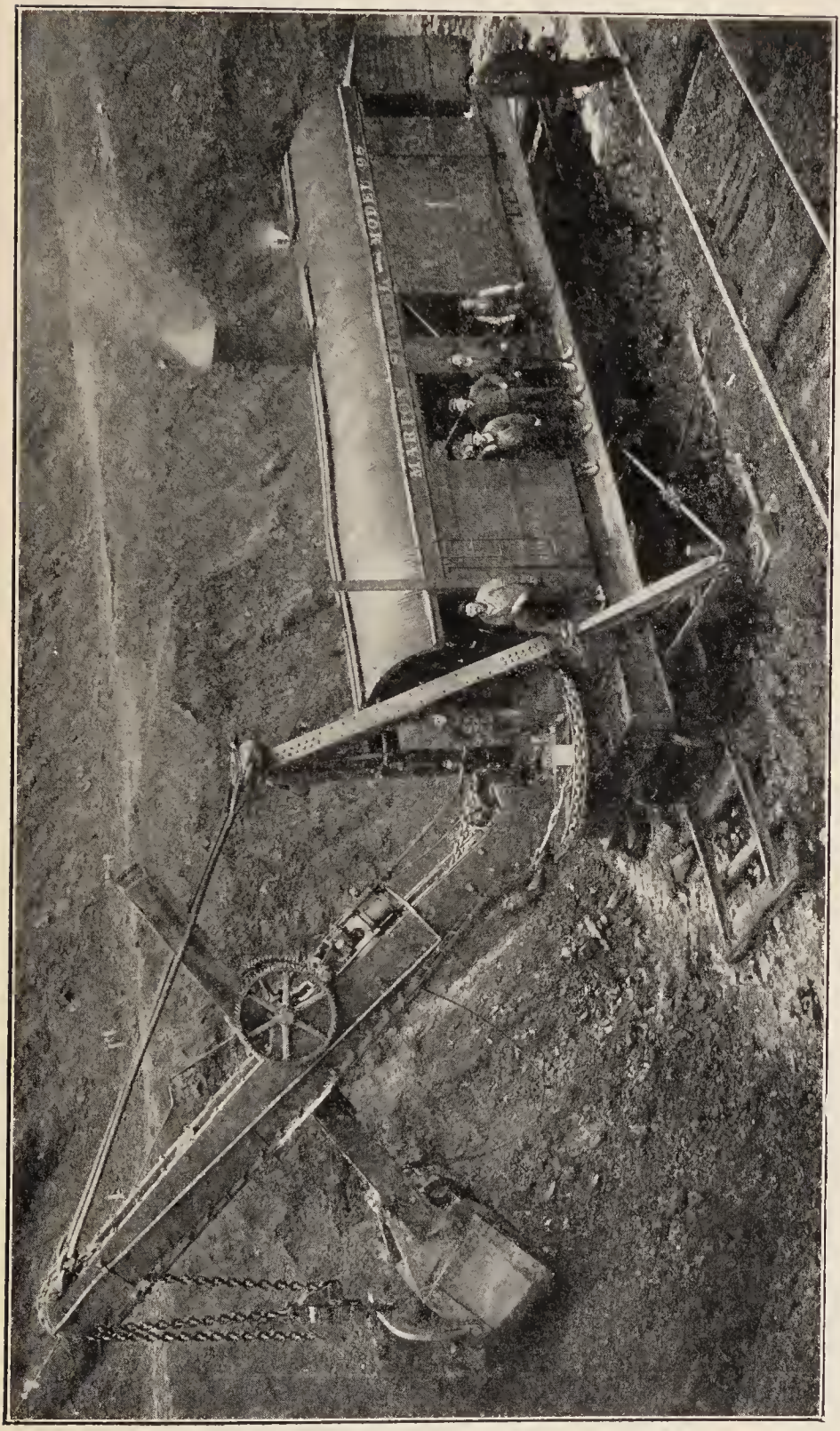


FIG. 4.—STEAM SHOVEL LOADING SOFT ORE.

man, but is mined, charged, and discharged in units of several tons each by specially designed machinery.

The mining and transportation of this great amount of material is in itself a mighty industry, every advance in which has contributed in no small share to the increasing volume and importance of the iron, steel, and other industries of the United States.

Mining.—Some of the Lake Superior deposits lie near the surface and are therefore cheaply mined. This is especially true of the soft, earthy deposits of the Mesabi range, which are sometimes worked in great open cuts, the ore being loaded upon cars by mammoth steam shovels, or sometimes by the caving method, the ore falling by gravity into cars situated in underground tunnels. The massive, or rock, ores are more costly to extract, and the utmost skill of American blast-furnace men has been exercised to employ as large a portion of the earthy ores as possible without choking up the furnace. In other countries, especially in Germany, the practice of agglomerating fine ores into briquettes is becoming more prevalent.

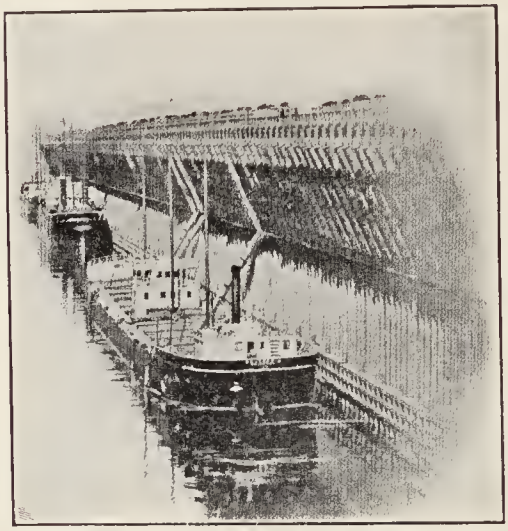


FIG. 5.—LOADING AN ORE BOAT.

Transportation.—On the lake the ore is transported in boats capable of taking a load of 10,000 or 13,000 tons of ore each. The hatches of these great boats are placed such a distance apart that the hinged ore chutes of the bins may be swung down and, when the gates are opened, the ore allowed to flow directly into the hold of the vessel. In a few minutes the vessel has received her full cargo and is ready to start on its long journey down the chain of inland lakes.

Unloading.—The unloading of boats is accomplished with almost as great celerity as the loading, and by means of mechanical unloading machinery a steamer containing as much as 10,300 tons of ore has been completely discharged in 4 hours and

30 minutes. Nor is any time wasted in coaling the vessel for a second journey up the lakes and back. Great machines pick up whole railroad cars of fuel and empty them bodily into the chute

FIG. 6.—BROWN-HOIST APPARATUS UNLOADING AN ORE BOAT.

which connects with the bunkers of the vessel, many of the ore steamers being so constructed that this wholesale loading of coal can go on at the same time that ore is being discharged.

FIG. 7.—HULETT ELECTRIC UNLOADER.

Prices.—Iron ores are divided into two great classes, known as "Bessemer" and "Non-Bessemer"; in the former class are those ores in which the percentage of iron is more than 1000

times the percentage of phosphorus. This name arises through the circumstance that only when the phosphorus is as low as this can we make from them a steel, with the blast furnace followed by the acid Bessemer process, with phosphorus under 0.100 per cent. The price of Bessemer ores is about 75 cents per ton more than non-Bessemer ores on this account. At present (1911) Mesaba Bessemer ores sell at about $5 per ton, which is twice the price they commanded 12 to 15 years ago.

Handling Raw Material at a Modern Furnace

Behind the blast furnace are situated long rows of storage bins, one of which is shown in elevation in Fig. 9. These bins are filled by bottom-dumping railroad cars which bring the ore to the furnaces, or by mechanical apparatus from the great piles of ore stored conveniently near. Between and under these two rows of bins runs a track on which ore larries are transferred back

FIG. 8.—ORE-HANDLING MECHANISM AT BLAST FURNACE.

and forth, being first filled with a weighed amount of ore, limestone, or fuel, and then switched into a position from which they can deposit their contents into the loading skip of the blast furnace.

Loading the Furnace.—The next step in the handling of the raw material is to bring the ore, together with the necessary fuel and flux, into the mouth of the huge furnace that is to convert it into pig iron. In one of the big modern American furnaces, working at top speed, the amount of material which must be dumped into the top during 24 hours will frequently exceed 2000 tons, and the charging must go on for 365 days a year with never a delay of more than a few minutes at a time.

In the modern type of furnace this loading is accomplished altogether by mechanism operated and controlled from the ground level, and no men are required to work at the top of the

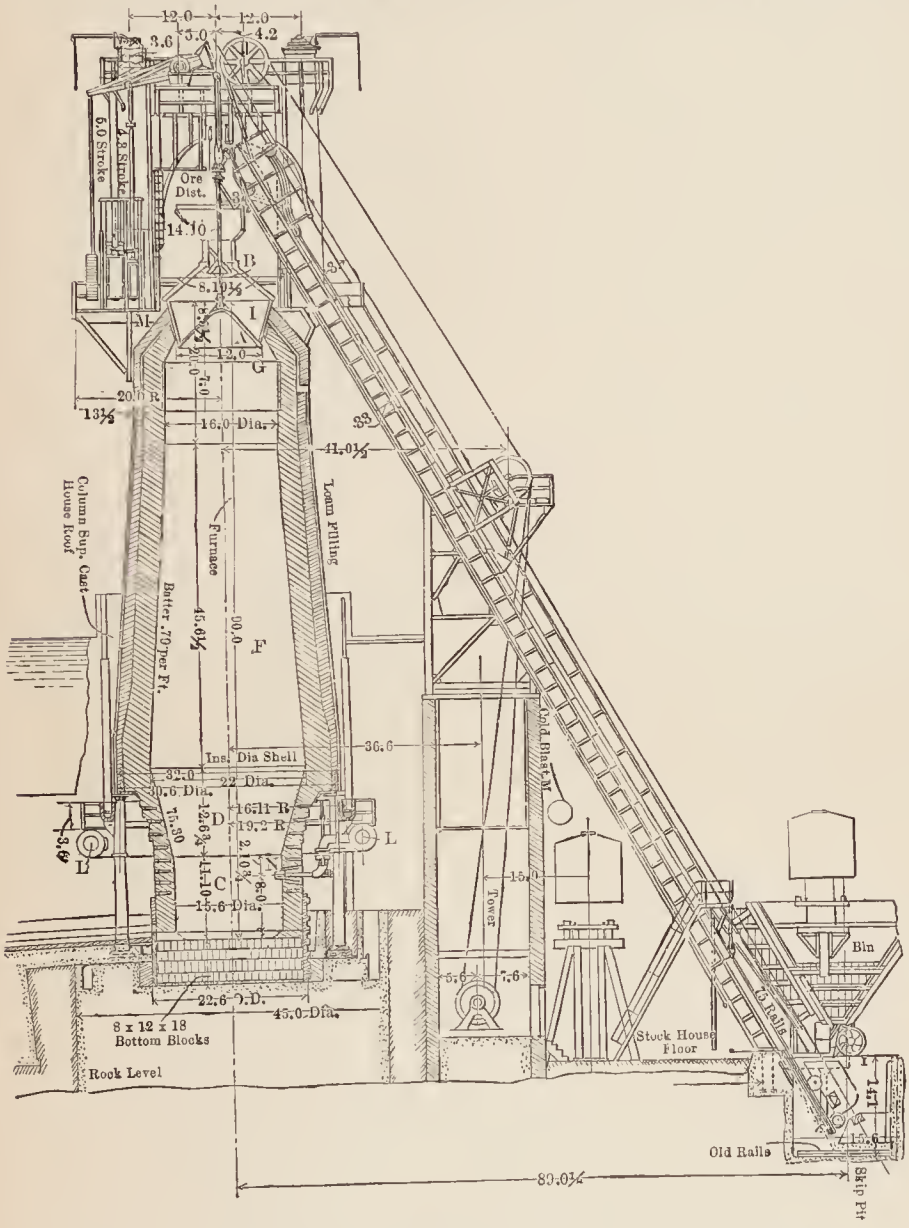


FIG. 9.—CROSS-SECTION OF BLAST FURNACE AND SKIP HOIST.

furnace. In Fig. 9 is a section of such a furnace showing one method of loading—a double, inclined skipway extending above the top of the furnace. One skip is seen discharging its load of ore, or fuel and flux, into the hopper, while the second skip is at the bottom of the incline ready to be loaded with its charge.

Double Bell and Hopper.—The upper hopper of the furnace is closed at the bottom by an iron cone, known as a "bell." This bell is held against the bottom of the hopper by the counter-weighted lever shown, and is opened by operating the cylinder *M*, to allow the charge to fall into the main hopper, *I*, of the blast furnace. In this way the hopper of the furnace is progressively filled with ore, flux, and fuel. This hopper, *I*, is also closed at the bottom by a similar bell, *A*. The operation of this bell is also controlled from the ground, and when a charge has been deposited in the hopper it is opened and the contents allowed to fall in an annular stream, distributing itself on top of the material already in the furnace which is within a few feet of the bottom of the bell. As the upper bell, *B*, is now held up against the bottom of the upper hopper, there is never a direct opening from the interior of the blast furnace to the outer air, so that the escape of gas, resulting formerly in the long flame rising from the top of the blast furnace whenever material was dropped into the interior, no longer occurs at our modern plants.

This is not the only means of handling the raw material for the blast furnace. Several varieties of mechanism are extensively used, but the description given heretofore will serve to illustrate the general principles of labor-saving mechanisms in connection with charging the blast furnace. The details of the distribution are of the utmost importance and largely affect the production, the quality of iron, the coke consumption, and, above all, the life of the lining. Cases are on record where apparently trivial changes in this detail have revolutionized the work of the furnace.

The Blast Furnace and Accessories

The blast furnace itself consists of a tall cylindrical stack lined with an acid (silicious) refractory fire-brick, the general form and dimensions being shown in Fig. 9. The hearth or crucible is the straight portion occupying the lower 8 ft. of the furnace. Above that extends the widening portion, called the bosh, which reaches to that portion in the furnace having the greatest diameter. The stack extends throughout the remainder of the furnace, from the bosh to the throat. The brickwork of the hearth is cooled by causing water to trickle over the outside surface.

Tuyeres.—Through the lining of the furnace, just at the top of the hearth, extend the tuyeres—8 to 16 pipes having an

internal diameter of 4 to 7 in., through which hot blast is driven to burn the coke and furnish the heat for the smelting operation. The "tuyere notches," or openings through which the tuyere pipes enter, as well as the tuyeres themselves, are surrounded by hollow bronze rings, through which cold water is constantly flowing to protect them from melting at the inner ends. The number and size of the tuyeres is in proportion to the diameter of the hearth, the volume and pressure of the blast, etc., the blast being given sufficient velocity to carry it, distributed as evenly as possible, to the very center of the furnace.

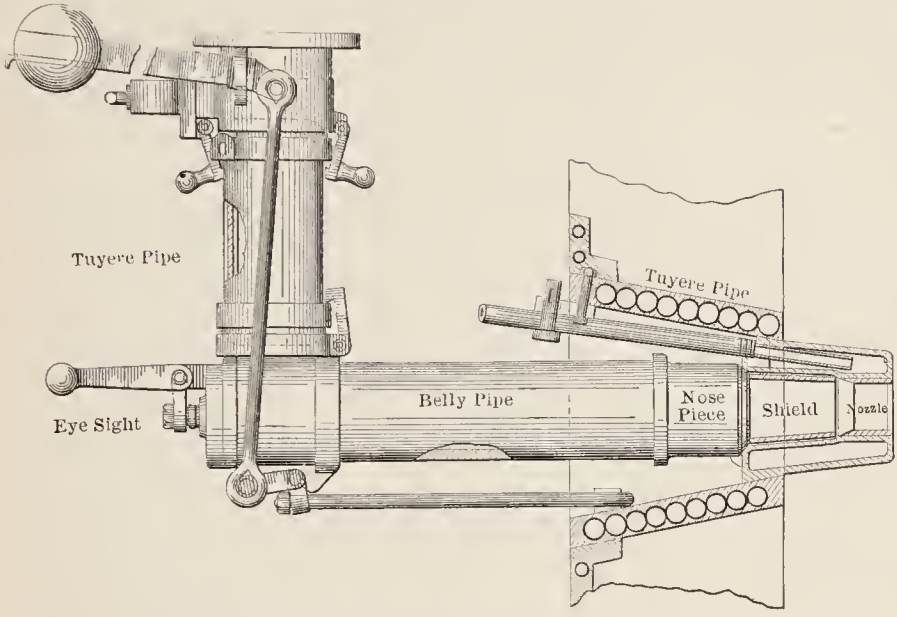


FIG. 10.—PARTS OF A BLAST FURNACE TUYERE.

Discharge Holes.—On the side of the furnace, and 30 to 40 in. below the level of the tuyeres, the "cinder notch" or "monkey" is situated. This is protected by a water-cooled casting, and the hole is closed by forcing into it an iron plug around which the cinder chills and makes a tight joint. The level of the tuyeres is the point above which the cinder must not be allowed to accumulate.

In the front, or breast, at the very bottom level of the crucible, is the iron tap-hole, from which all the liquid contents of the furnace can be completely drained. This is a large hole in the brickwork, and is closed with several balls of clay.

Bosh.—The hottest part of the furnace is near the tuyeres and a few feet above them. In order to protect the brickwork of

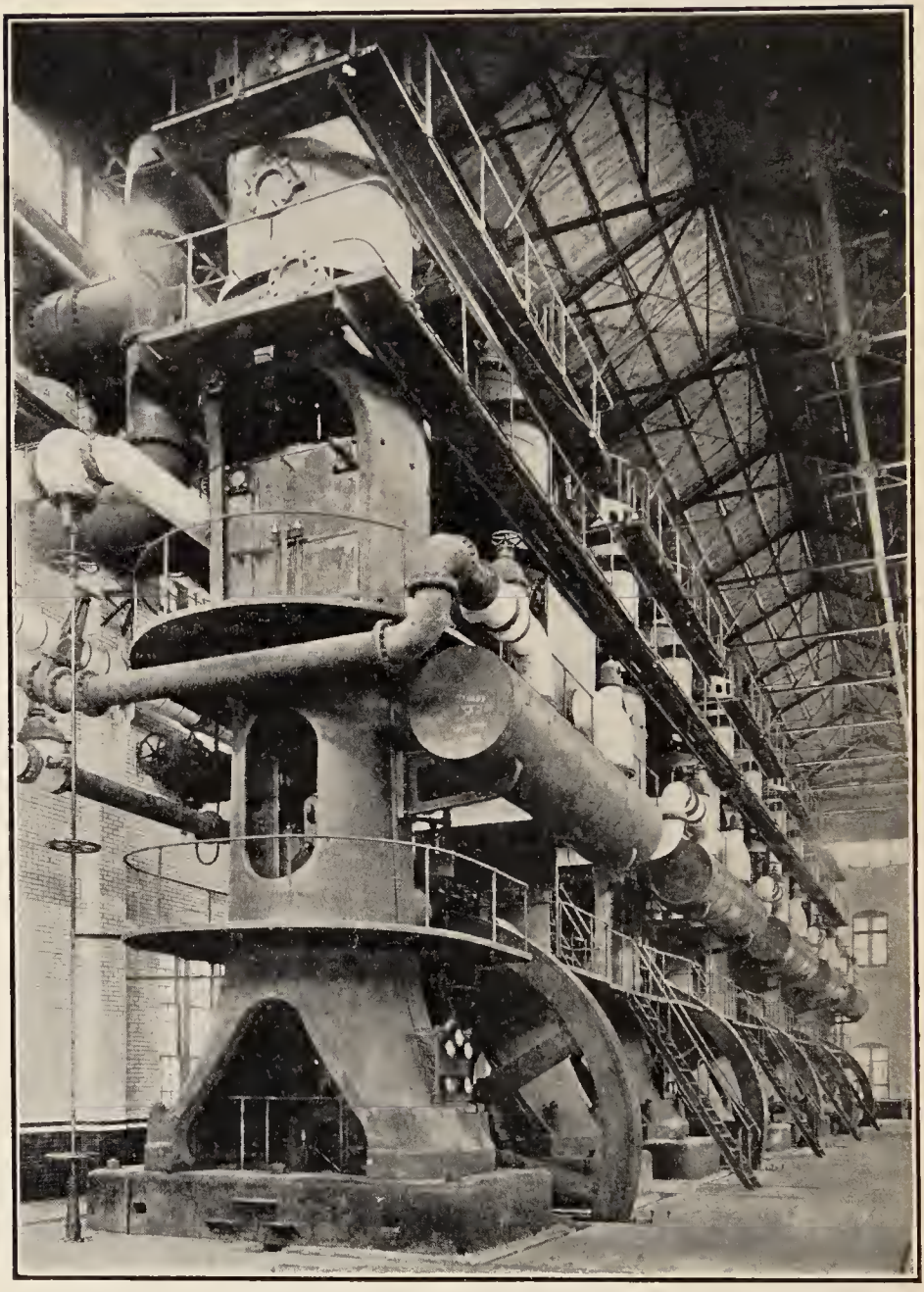


FIG. 11.—A BATTERY OF BLAST FURNACE BLOWING ENGINES.

the bosh from this heat, a number of hollow wedge-shaped castings are placed therein, through which cold water circulates. The brickwork is furthermore protected by a deposition of a layer of carbon, similar to lampblack, on its internal surface, covered by a layer of a sort of slag, or cinder, replacing part of the brickwork. The deposition of carbon comes about through the reaction of the furnace operation itself, in the following manner: For the correct conduct of the smelting operation, and especially for carrying of the sulphur in the slag, it is necessary that a very powerful reducing influence must exist; this reducing influence is produced by an excess of coke, and one of its results is the precipitation of finely divided carbon on the internal walls of the furnace. It is this thin layer of cinder and carbon which is most effective in protecting the acid lining of the furnace from the corrosive action of the basic furnace slag. Other methods of protecting the bosh walls are in use, one of the most successful being a plain steel jacket thoroughly cooled externally by sprays and lined with a single course of brick. This avoids the benching or stepping which occurs with the construction above described.

Hot Blast.—The air for smelting is driven into the furnace by immense blowing engines ranging up to 2500 H. P. each, and capable of compressing 50,000 to 65,000 cu. ft. (=4875 lb.[1]) of free air per minute to a pressure of 15 to 30 lb. per sq. in., which is about what one furnace requires. It actually requires about 4 to 5 tons of air for each ton of iron produced by the furnace. After leaving the engines and before coming to the furnace, the air is heated to a temperature of 425 to 650° C. (800 to 1200° F.) by being made to pass through the hot-blast stoves.

Hot-blast Stoves.—Each furnace is connected with four or five stoves. These are cylindrical tanks of steel about 110 ft. high and 22 ft. in diameter, containing two or more fire-brick chambers. One of these chambers is open, and the others are filled with a number of small flues (see Fig. 12). Gas and air are received in the bottom of the open chamber, *B*, in which they burn and rise. They then pass downward through the several flues in the annular chamber surrounding *B*, and escape at the bottom to the chimney as waste products. In passing through the stove they give up the greater part of their heat to the brickwork. After this phase is ended, the stove is ready to heat the blast.

[1] At 70° F. and atmospheric pressure, each 1000 cu. ft. of air weighs 75 lb.

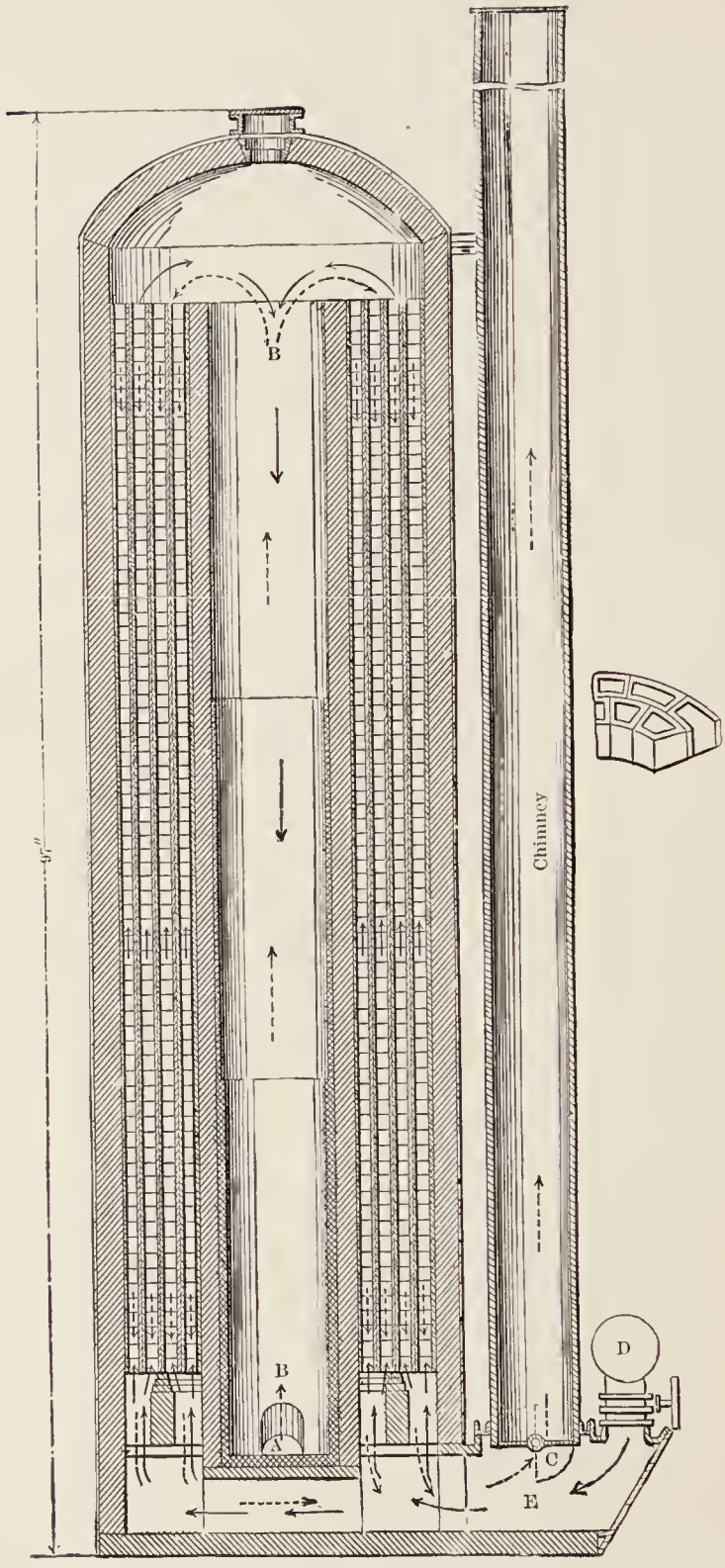


FIG. 12.—HOT-BLAST STOVE. From Howe, "Iron, Steel and other Alloys."

The blast from the blowing engine enters at the bottom of the flues, *E*, passes up through the outer chamber, and down through *B* to the furnace. In this passage it takes up the heat left in the brickwork by the burning gas and air. Sometimes there are three passes, instead of two as described. In a blast-furnace plant, one stove is heating the blast while the other three are simultaneously in the preparation stage, burning gas and air. By changing once an hour a pretty regular blast-temperature is maintained. The gas used for the heating is the waste gas from the blast furnace itself, which amounts to about 90,000 cu. ft. per minute at a temperature of 235° C. (450° F.), and has a calorific power of about 85 to 95 B. T. U. per cubic foot. The latent and available heat of this gas is equivalent to approximately 50 per cent. of that of the fuel charged into the furnace. Only about 30,000 cu. ft., or one-third of this gas, is needed for keeping the stoves hot, and the remaining two-thirds is used to produce power.

Power from Waste Gas.—The waste gas comes down the downcomer *T*, Fig. 13, deposits dirt in the dust-catcher *W*, is carefully cleaned and scrubbed, and is then led to the stoves or power producer. This gas varies in composition, but will average about 61 per cent. nitrogen, 10 to 17 per cent. CO_2, and 22 to 27 per cent. CO. The latter can be burned with air to produce heat.

$$CO + O = CO_2 \text{ (generates 68,040 calories).}$$

If burned under boilers, the available gas will generate enough power to operate the blowing engines, hoisting mechanism, and other machinery used in connection with the furnace. At several plants the gas available for power is cleaned carefully and utilized in gas engines, whereby much more power is obtained, the excess being usually converted into electricity and transmitted to more distant points.

Smelting Practice and Products

The furnace is filled with alternate layers of fuel, flux, and ore, down to the top of the smelting zone. The exact location of this zone will be dependent upon the volume and pressure of blast, size of furnace, character of slag made, etc., but will extend from the level of the tuyeres to a few feet above them, or about to the top of the bosh. It will require perhaps 15 hours for the material to descend from the top of the furnace to the smelting zone. During this descent, it is upheld partly by the resistance of the

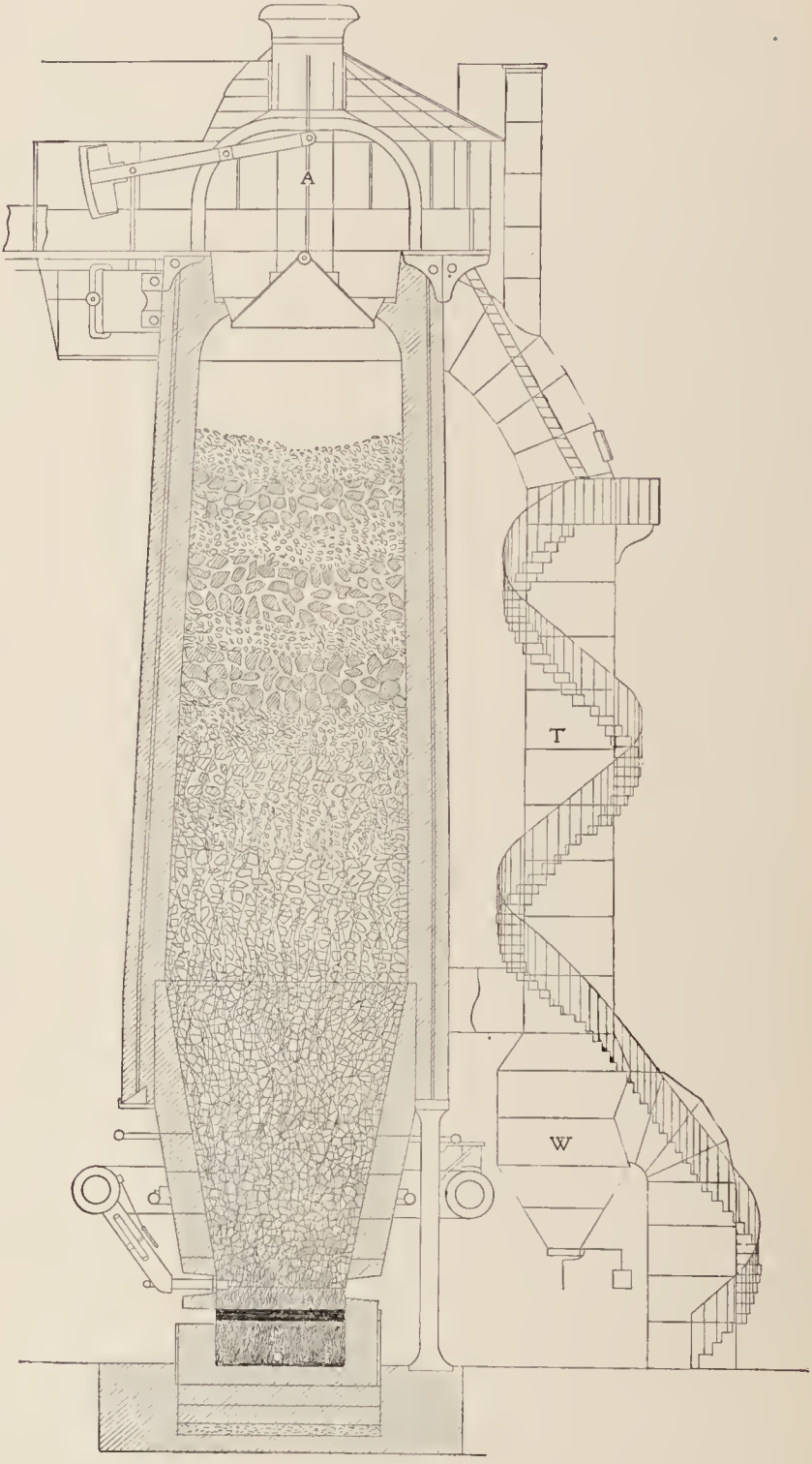


FIG. 13.

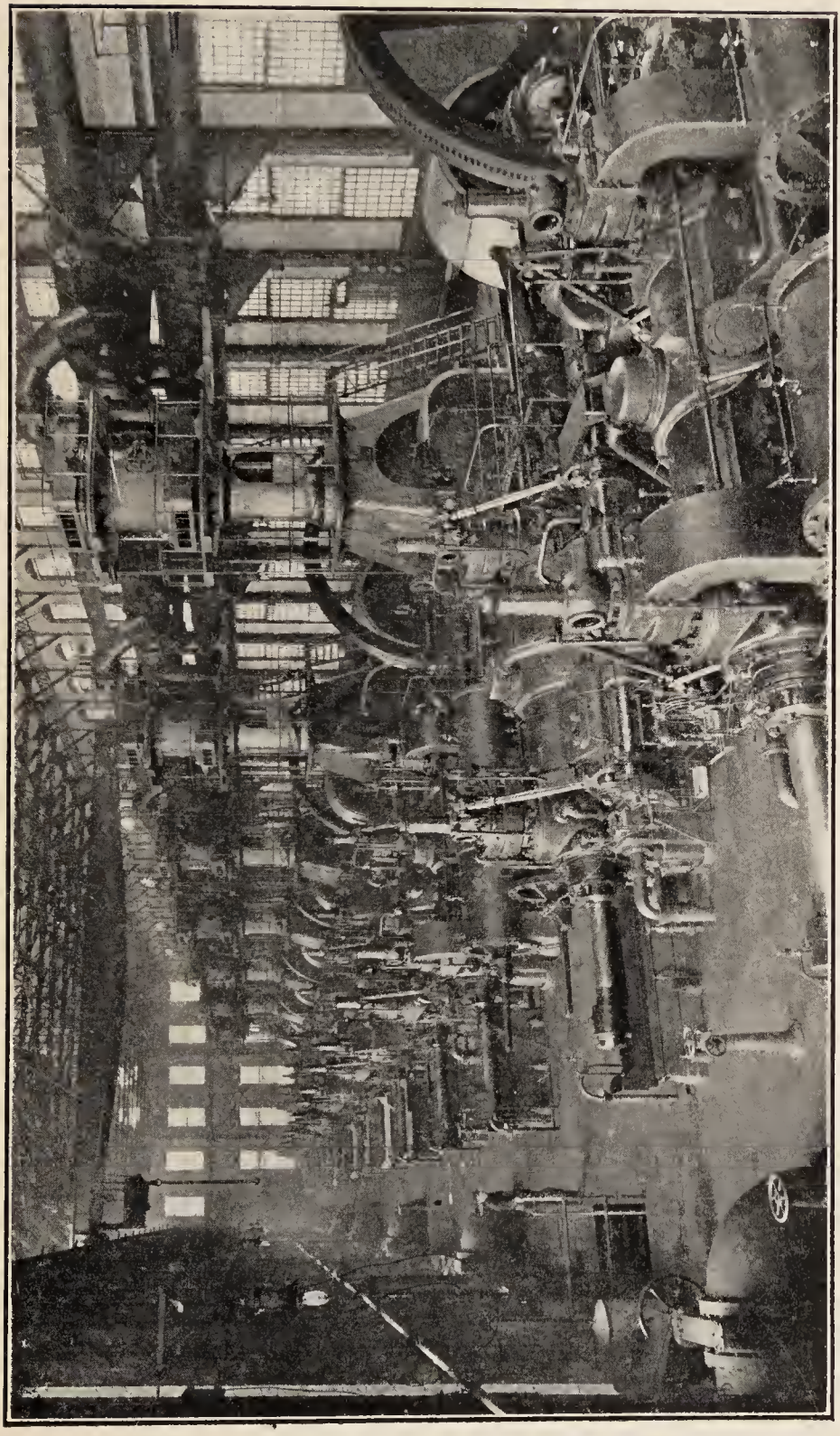


FIG. 14.—BLOWING ENGINE HOUSE OF THE LACKWANNA STEEL COMPANY.

uprushing column of hot gases,[1] partly by its friction on the walls of the furnace, and partly by the loose column of coke which extends through the smelting zone and to the bottom of the furnace, and which alone resists melting in the intense heat of this

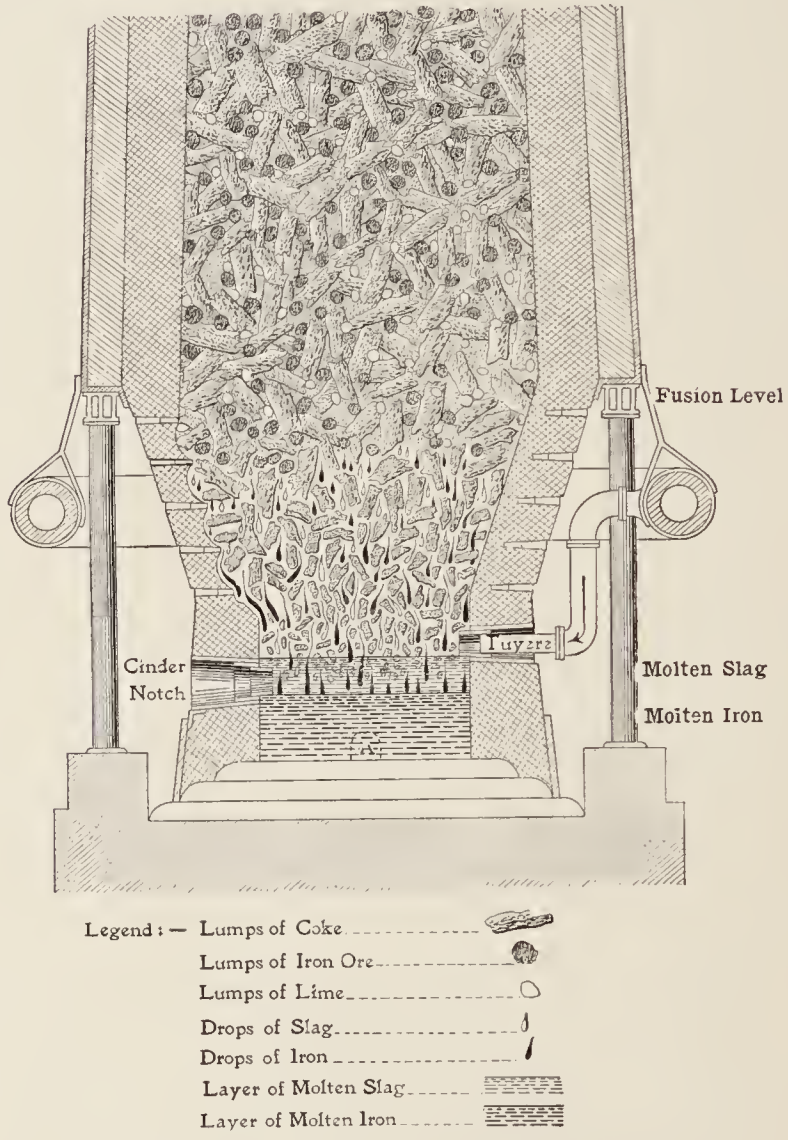


FIG. 15.—From Howe, "Iron, Steel, and other Alloys."

zone. The blast entering the furnace through the tuyeres, consists of 23 per cent. by weight of oxygen and 77 per cent. by weight of nitrogen, together with varying amounts of water

[1] The full drop from the blast pressure to practically atmospheric pressure at the throat represents the resistence of the stock to the upward passage of the gas and of course this represents also the resistance offered by the gas to the descent of the stock. This resistance is in many cases nearly equal to the weight of the stock.

vapor from moisture in the air (see page 32). The nitrogen is practically inert chemically and performs no function other than that of absorbing heat in the smelting zone and giving it out at higher levels. The oxygen attacks all the coke in the smelting zone and as much of it below the level of the tuyeres as is not covered by accumulations of iron and slag in the hearth, producing a large volume of carbon monoxide gas (CO) and a temperature which may exceed 3000° F.[1] The CO and nitrogen pass up between the particles of solid material, to which they give up the greater part of their heat. The former also performs certain chemical reactions, and thus in both ways the rising column of gases prepares the charge for its final reduction in the smelting zone.

Chemical Reactions in the Upper Levels.—As soon as the iron ore enters the top of the furnace, two reactions begin to take place between it and the gases:

(1) $2Fe_2O_3+8CO=7\ CO_2+4Fe+C$;
(2) $2Fe_2O_3+\ CO=2\ FeO+Fe_2O_3+CO_2$;

and this continues with increasing rapidity as the material becomes hotter. The carbon formed by reaction No. 1 deposits in a form similar to that of lampblack on the outside and in the interstices of the ore. This reaction, however, is opposed by two reactions with carbon dioxide gas:

(3) $Fe+CO_2=FeO+CO$;
(4) $C\ +CO_2=2CO$.

Reaction No. 3 begins at a temperature of about 300° C. (575° F.), which is met with about 3 or 4 ft. below the top level of the stock; and No. 4 begins at about 535° C. (1000° F.), or 20 ft. below the stock line. Reaction No. 4 is so rapid that the deposition of carbon ceases at a temperature of 590° C. (1100° F.). All the way down the ore is constantly losing a proportion of its oxygen to the gases. At higher temperatures than 590° C., FeO is stable and practically all of the Fe_2O_3 has been reduced.

(5) $Fe_3O_4+CO=3FeO+CO_2$.

The reaction between iron oxide and solid carbon begins at 400° C. (750° F.).

(6) $Fe_2O_3+3C=2Fe+3CO$.

$$C+O_2=CO_2$$
$$CO_2+C=2CO$$

[1] It is of minor importance whether the CO gas is formed directly or as a result of the two following reactions:

At 700° C. (1300° F.) solid carbon begins to reduce even FeO:

$$(7)\ FeO + C = Fe + CO.$$

Practically all the iron is reduced to a spongy metallic form by the time the temperature of 800° C. (1475° F.) is reached. This is about 45 ft. from the stock line and less than 30 ft. above the tuyeres. At 800° C. the limestone begins to be decomposed by the heat, and only CaO comes to the smelting zone:

$$(8)\ CaCO_3 = CaO + CO_2.$$

The foregoing facts are summarized in Fig. 16, which is adapted from H. H. Campbell, with certain changes.[1] It is not to be supposed that these figures are exactly correct for the different levels, and it is probable that they change from day to day and from furnace to furnace, but a general idea may be obtained from this sketch. It will be seen that the upper 15 or 20 ft. of stock is a region of Fe_2O_3 and Fe_3O_4, gradually being converted to FeO by CO gas, and forming quantities of CO_2 gas. If these reactions were the only ones, the top gases would contain no CO and would have no calorific power, but reaction No. 1 produces both metallic iron and carbon, both of which reduce CO_2 and thus waste much energy, as far as the blast furnace is concerned:

Reaction No. 3, $Fe + CO_2 = FeO + CO$, absorbs 2340 calories, but wastes 68,040 calories.

Reaction No. 4, $C + CO_2 = 2CO$, absorbs 38,880 calories.

From 20 to 35 ft. below the stock line is the region of FeO, gradually being converted to metallic iron sponge by carbon. At the lower level of this zone the limestone loses its CO_2, which joins the other furnace gases. From 35 ft. down to the smelting zone is the region of metallic iron. This spongy iron is impregnated with deposited carbon which probably to some extent soaks into it and dissolves, in a manner like in nature but not in degree to the way ink soaks into blotting-paper. This carburization of the iron reduces its melting-point and causes it to become liquid at a higher point above the tuyeres than it otherwise would.

On reaching the smelting zone the iron melts and trickles quickly down over the column of coke, from which it completes its saturation with carbon. At a corresponding point the lime unites with the coke ash and impurities in the iron ore, forming a fusible slag which also trickles down and collects in the hearth.

[1] See pp. 54 and 62 of Book No. 2.

It is during this transit that the different impurities are reduced by the carbon, and the extent of this reduction determines the characteristics of the pig iron, for in this operation, as in all smelting, reduced elements are dissolved by the metal, while those in the oxidized form are dissolved by the slag. Only one exception occurs, namely, that iron will dissolve its own sulphide (FeS) and, to a less extent, that of manganese (MnS), but not that of other metals, as, for instance, CaS.

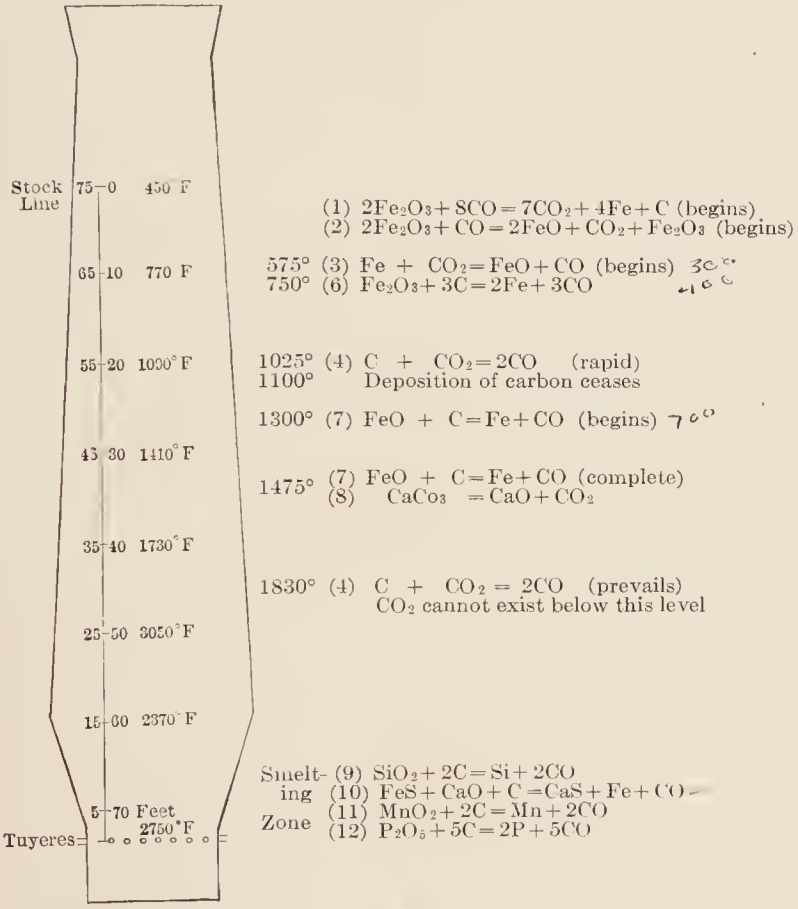


FIG. 16.—DIAGRAM SHOWING CHEMICAL ACTION IN BLAST FURNACE.

Chemical Reactions in the Smelting Zone.—There is always a large amount of silica present in the coke ash, and some of this is reduced according to the reaction:

$$(9)\quad SiO_2+2C=Si+2CO.$$

The extent of this reaction will depend on the length of time the iron takes to drop through the smelting zone, the relative intensity of the reducing influence, and the avidity with which the slag

takes up silica. A slag with a high melting-point will trickle sluggishly through the smelting zone and cause the iron to do the same, to some extent, thus giving it more chance to take up silicon. A higher temperature in the smelting zone, which increases disproportionately the avidity of carbon for oxygen, will promote reaction No. 9. We can produce this higher temperature by supplying hotter blast. A larger proportion of coke to burden[1] will further promote this reaction, because this not only increases the amount of the reducing agent, but also raises the temperature and, therefore, the chemical activity of this agent. Thus the coke has both a physical and a chemical influence in increasing the intensity of the reduction in the smelting zone. A basic slag, because of its avidity for silica, will oppose reaction No. 9; it is one of the principal means of making low-silicon pig iron. This is in spite of the fact that the basic slags are sluggish, and therefore trickle slowly through the smelting zone, thus exposing the silica longer to reducing influence, and also increasing the temperature of the materials in this zone (1) by causing them to pass through it more slowly and absorb more heat, and (2) by reducing the level of the smelting zone nearer to the tuyeres, which confines the intense temperature to the smaller area, or, in other words, diminishes the passage of heat upward.

Sulphur comes into the furnace chiefly in the coke. It is partly in the form of iron sulphide (FeS), and partly in the form of iron pyrites (FeS_2), which loses one atom of sulphur near the top of the stock and becomes FeS, which will dissolve in the iron unless converted to sulphide of calcium (CaS). This is brought about, according to the explanation of Professor Howe, by the following reaction:

$$(10)\quad FeS + CaO + C = CaS + Fe + CO.$$

CaS passes into the slag, and the odor of sulphur is very strong when the slag is running from the furnace. It is evident from reaction No. 10 that intense reduction, which increases the silicon in the iron, has the contrary effect on the sulphur, and this explains the common observation that iron high in silicon is liable to be low in sulphur. Indeed, this relation is so constant that it is almost a rule. There are two exceptions, however: (1) Increasing the proportion of coke has a doubly strong influence in putting silicon in the iron. As regards sulphur, on the

[1] The burden is the amount of material that the coke has to melt. We lighten the burden by increasing the amount of coke, and vice versa.

other hand, it has a self-contradictory effect; by increasing the amount of sulphur in the charge it tends to increase it in the iron, which is partly or wholly counteracted by its effect in reaction No. 10. (2) A basic slag may hold silicon from the iron, and it also holds sulphur from the iron by dissolving CaS more readily. In other respects the conditions which make for high

TABLE II.—COMPOSITION OF BLAST-FURNACE SLAGS.

From H. H. Campbell. P. 50 of No. 2.

	Slag							Iron		Remarks
	SiO_2	Al_2O_2	CaO	MgO	FeO	S	Total not including S	Si	S	
1	33.10	14.92	40.76	9.67	....	....	98.45	3.37	tr.	Cuban ore, Hot furnace.
2	32.27	14.57	41.02	10.30	....	....	98.16	3.18	tr.	Cuban ore, Hot furnace.
3	24.26	11.53	40.25	13.28	....	....	98.32	4.81	.01	Cuban ore, Hot furnace.
4	32.68	13.50	43.28	9.44	....	....	98.90	1.25	.06	Cuban ore, Warm furnace.
5	32.28	9.38	46.95	9.52	....	....	98.13	0.70	.11	Cuban ore, Cool furnace.
6	34.50	7.94	46.47	10.47	....	....	99.38	0.69	.05	Cuban ore, Cool furnace.
7	34.98	12.05	41.33	9.62	....	....	97.98	2.60	.03	Spanish ore, Hot furnace.
8	34.70	11.44	41.27	9.96	....	....	97.37	2.32	.02	Spanish ore, Hot furnace.
9	33.68	11.93	45.96	6.69	....	....	98.26	1.27	.02	Spanish ore, Hot furnace.
10	29.86	12.04	45.20	11.41	....	....	98.51	1.27	.02	Spanish ore, Hot furnace.
11	28.95	12.04	49.30	8.46	....	....	98.75	0.57	tr.	Spanish ore, Cool furnace.
12	30.62	10.47	49.13	7.49	....	....	97.71	0.26	.02	Spanish ore, Cool furnace.
13	32.55	11.13	47.16	6.61	....	....	97.45	0.15	.03	Spanish ore, Cool furnace.
14	30.08	11.44	46.36	8.76	....	....	96.64	0.58	.03	Spanish ore, Cool furnace.
15	31.46	11.50	44.85	10.41	....	....	98.22	0.20	.07	Spanish ore, Cool furnace.
16	36.08	12.85	41.69	7.25	0.54	1.62	98.41	2.15	.020	Hot furnace
17	37.19	12.65	35.47	11.32	0.90	1.70	97.53	1.92	.029	Lake ore — Fairly hot
18	36.86	10.74	42.46	6.62	0.63	1.54	97.31	1.50	.028	and part — Fairly hot
19	32.06	11.97	42.46	10.25	0.63	1.76	97.37	1.59	.032	anthracite — Fairly hot
20	33.57	10.65	44.11	8.55	0.81	1.74	97.69	0.94	.017	Coal; — Normal
21	35.38	11.76	38.19	12.32	0.90	1.60	98.53	1.13	.040	mostly — Normal
22	36.35	10.21	40.10	10.95	0.99	1.28	98.60	0.66	.095	Connells- — Cool
23	33.70	12.56	38.12	11.60	0.32	0.96	98.30	0.50	.101	ville coke — Cool
24	35.11	14.21	22.48	22.38	....	....	100.12	1.37	.048	Lake ore — Av. of 8 wks.
25	35.10	14.75	27.95	22.28	....	....	100.08	1.85	.038	and Con- — Av. of 7 wks
26	35.84	14.34	32.71	17.46	....	....	100.35	1.60	.034	nelsville — Av. of 7 wks.
										coke.
	Averages for hot furnaces:									
	33.21	13.67	40.68	11.08	....	....	98.64	3.79	tr.	Cuban ore.
	34.84	11.75	41.30	9.79	....	....	97.68	2.46	.025	Spanish ore.
	31.77	11.98	45.58	9.05	....	....	98.38	1.27	.020	Spanish ore.
	35.55	12.05	40.52	8.86	0.68	1.66	97.66	1.79	.027	Lake ore.
	Averages for moderate or cool furnace:									
	33.15	10.27	45.57	9.81	....	....	98.80	0.88	.07	Cuban ore.
	30.73	11.32	47.36	8.35	....	....	97.75	0.35	.03	Spanish ore.
	34.75	11.30	40.12	10.86	1.26	1.40	98.29	0.81	.063	Lake ore.
	35.35	14.43	29.69	20.71	....	....	100.18	1.61	.040	Lake ore.

silicon make also for low sulphur. Particularly is this true of a high temperature in the smelting zone, and the term "hot iron" has come to be synonymous in the minds of blast-furnace foremen with iron high in silicon and low in sulphur.

Manganese is reduced by the following reaction:

$$(11)\quad MnO_2 + 2C = Mn + 2CO.$$

The amount of manganese in the iron is dependent, to a certain extent, upon the character of the ores charged, but it may be controlled somewhat by the character of slag made, because an acid slag will carry a large amount of manganese away in the form of silicate of manganese ($MnSiO_3$).

With a certain unimportant qualification, the amount of phosphorus in the iron is controlled by the character of raw materials charged, and districts or countries having high-phosphorus ores must make high-phosphorus irons. This is not an insuperable objection, because the presence of phosphorus, even up to 1.5 per cent., is desired in certain irons for foundry use, and the basic processes for making steel can remove this element.

The chemical influence of the blast furnace is a strongly reducing one, and this is produced in order, first, to reduce the iron from the ore; second, to get rid of the sulphur, and third, to saturate the iron with carbon. Many attempts have been made to provide a process wherein the reducing influence was not so strong, and thus to produce a purer material than pig iron, because it is the intensity of the reduction which contaminates the iron with carbon and silicon. The great weakness of all such processes, however, is that they do not get rid of the sulphur, which is the most objectionable impurity that iron is liable to contain and which is not cheaply removed by any process after once it makes its way into the iron. Finally, to saturate the iron with carbon renders the blast-furnace operation very much cheaper, because pure iron melts at a temperature much higher than can readily be obtained in the furnace, and iron is handled much more cheaply molten than in the solid or pasty state. Even the presence of silicon is an advantage, as we shall see in Chapter XII.

Drying the Blast.—The water vapor blown into the furnace (derived from the moisture of the air) is equivalent to from 1/3 to 2 gal. of water per 10,000 cu. ft. of blast, or 1 1/3 to 8 gal. per minute, depending on the humidity of the atmosphere. Though

this steam is as hot as the blast, it materially cools the smelting zone of the furnace by dissociating there:

$$H_2O + C = 2H + CO \text{ (absorbs 28,900 gram calories)};$$

or 1 lb. of steam absorbs 7,110,000 calories. The hydrogen and oxygen reunite in a cooler part of the furnace and return the same amount of heat, but this does not compensate for that taken away from the smelting zone, where it is most needed. For this reason several American and European plants have adopted James Gayley's process of drying the air by refrigeration before it is drawn into the blowing engine. This results in valuable saving in fuel and greater regularity of furnace working. In fact, so great is the economy shown in this respect that there was a tendency at first to receive the results with skepticism.

The same condition prevailed upon the introduction of the hot blast, early in the last century, for the same reasons: That no explanation was forthcoming of the observation that the fuel saved in practice was so much greater in proportion than the heat saved or restored to the crucible. But it was pointed out by J. E. Johnson, Jr., in the discussion of Mr. Gayley's results, that certain functions of the smelting process can only be carried out above a certain "critical temperature," which was in fact the free-running temperature of the slag, and that the heat available above this temperature, and not the total heat developed in the furnace, was the measure of the economy that can be attained. Approximately speaking, the interval between the "critical temperature" and the theoretical combustion temperature, is the measure of this available heat, and as the critical temperature is, roughly speaking, four-fifths of the theoretical combustion temperature, any change which increased or decreased the latter by a given proportion, will increase or decrease the available heat by a proportion five times as great. This simple explanation enables us to calculate with accuracy the effect of any given change in known conditions.[1]

Johnson also pointed out that the theoretical combustion temperature might be increased by enriching the air in oxygen, instead of reducing the moisture in it, since this enrichment would increase the calorific efficiency. A Belgian blast furnace

[1] If further explanation of this argument is needed, it may be found in the following simile: Water boils at 212° F. If the temperature of a boiler is 262°, there is a certain pressure of steam; if we increase the temperature only 50°, we greatly increase the pressure; y + 50° appears small in comparison to 262°.

has recently adopted this type of practice, and the results will be watched with great interest, as well on practical as on theoretical grounds.

Slag Disposal.—The slag, on account of its lower specific gravity, floats in the bath of iron in the hearth and accumulates until it reaches nearly to the level of the tuyeres. The cinder-notch is then opened by withdrawing the iron plug and piercing the skull of chilled cinder with a steel bar, and the cinder drawn off down to the lever of the notch. This is done four or five times between each iron tap, i.e., each six hours. It flows down an inclined iron runner for a distance of 15 to 30 ft. and pours into an iron ladle on a standard-gage railroad track, whence it is drawn away by a locomotive and poured out on the slag dump. Slag varies in composition according to the will of the blast-furnace manager, and some typical analyses are given in Table II. Slags high in lime are sometimes treated with additional lime to make a good grade of Portland cement, known as "Puzzolini." The amount of cinder made will depend on the amount of silica, alumina, etc., in the ore, the amount of coke ash, and the amount of flux, which will also depend on the desired slag analysis. Under favorable circumstances, the slag may weigh slightly less than half the iron; under other conditions it may weigh nearly twice the iron, depending on the amount of impurity in the charge.

Weight of Slag.—The amount of slag may be calculated from the amount of lime (CaO) in the furnace, which may be calculated from the percentage of lime in the limestone and other materials charged into the furnace. Since all the lime charged goes into the slag, the amount of the latter will be equal to the weight of lime divided by the percentage of the lime in the slag. Thus, if we use per ton of iron 1300 lb. of limestone, containing 50 per cent. of lime, there will be 650 lb. of lime charged for every ton of iron made. If the slag made contains 40 per cent. lime, then the weight of slag will be $650/.40 = 1625$ lb. per ton of iron made.

Iron Disposal.—Immediately after the last "flushing," i.e., removal of cinder, the tap hole or iron notch is opened by several men drilling a hole in it with a heavy, pointed steel bar. Out of this notch flows 100 to 150 tons of liquid pig iron, with which is carried along 30 tons or so of slag. The "skimmer" is situated about a dozen feet from the front of the furnace. It is an iron

plate extending down almost to the bottom of the runner. The slag is deflected by this plate into a runner of its own, which leads it off to a slag ladle such as described before. The heavier pig iron flows under the skimmer and is distributed to six or seven brick-lined ladles on a standard-gage railroad track. It is then drawn away to the steel works, or, if not wanted there, is poured into iron molds at the pig-casting machine.

Mechanical Pig-Molding Machine.—There are several types of molding machine, but a common form is illustrated in Figs. 18–9, and consists of a long continuous series of hollow metallic molds carried on an endless chain. *D* is the pig-iron ladle pouring

FIG. 17.

metal into the spout, from whence it overflows into the molds as they travel slowly past. The pig iron chills quickly against the metallic molds, and by the time it reaches the other end of the machine, it consists of a solid pig of iron which drops into the waiting railroad car as the chain passes over the sheave. The pig iron is now in a form convenient for transportation or for storing until needed. The molds travel back toward the spout, underneath the machine and hollow side down. At the point *C* they are sprayed with whitewash, the water of which is quickly dried off by the heat of the mold, leaving a coating of lime inside to which the melted iron will not stick. This mechanical casting

is a great improvement over the former method of cooling iron in front of the blast furnace, because of the severity of the work which the former method involved and which, in hot weather, was well-nigh intolerable to human beings. It also gives pigs which are cleaner, i.e., freer from adhering sand. This silicious sand is objectionable, especially in the basic open-hearth furnace.

FIG. 18.—UEHLING PIG-CASTING MACHINE.

Sand-casting.—This method is still used at some furnaces, because of the capital needed to install machines and their high cost for repairs. Moreover, foundrymen often prefer the sand-cast pig because they are able to tell by the appearance of its fracture what grade of castings it will make, which they cannot well do with iron cast in metal moulds (see pages 318, 336). In

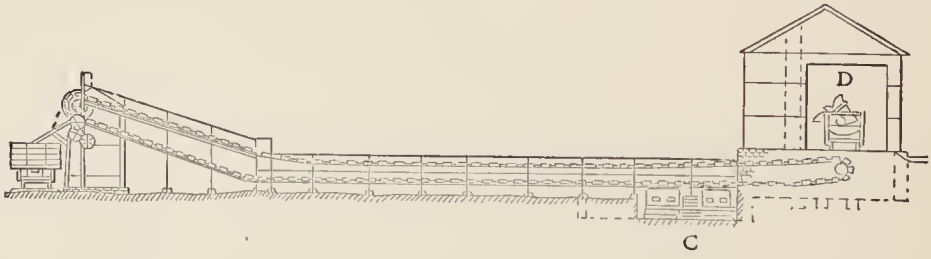


FIG. 19.—HEYL AND PATTERSON PIG-CASTING MACHINE.

the sand method, the cast house extends in front of the furnace and its floor is composed of silica sand, in which the molds or impressions to receive the liquid iron are made. The main runner extends from the taphole down the middle of the floor, and the space on either side of it is used alternately for alternate castings. The plan of the arrangement is shown in Fig. 20.

After cooling the iron, the pigs are broken away from the sows, which are also broken into pieces with a sledge, and then all is carried over and thrown into a railroad car. In making "basic iron"—i.e., iron for the basic open-hearth steel process—the moulds for the sows and pigs are permanently made of metal, so that the iron will not carry acid sand into the basic hearth.

Irregularities in Blast-furnace Working.—Although the management and control of the operation is in general as I have described it, the blast furnace is by no means a perfect machine, and great difficulties arise in the working of the furnace and in maintaining a uniform grade of product. The chief of these difficulties result from localized chilling of the semi-molten charge. This is most liable to happen in the upper part of the smelting zone, where a lump of pasty material may attach itself to the walls of the furnace. This has the effect of hindering the descent of that part of the charge above it and of deflecting the hot gases to other parts of the furnace. The result of the first action is to disarrange the order and evenness with which originally horizontal rings of stock come down into the hearth. The obstruction is also liable to receive chilled materials from above and to build itself out toward the center. When the furnace is working badly, these scaffolds may occur at two or more places at the same time and cantilever out toward the middle. This will cause a "hanging" of the charge, and may become so bad as to cause a complete arch over the smelting zone, through which it is impossible to drive the blast. Sometimes the scaffold may be broken down by suddenly cutting off the blast pressure and allowing the full weight of material in the furnace to come upon the obstruction; but sometimes it is neces-

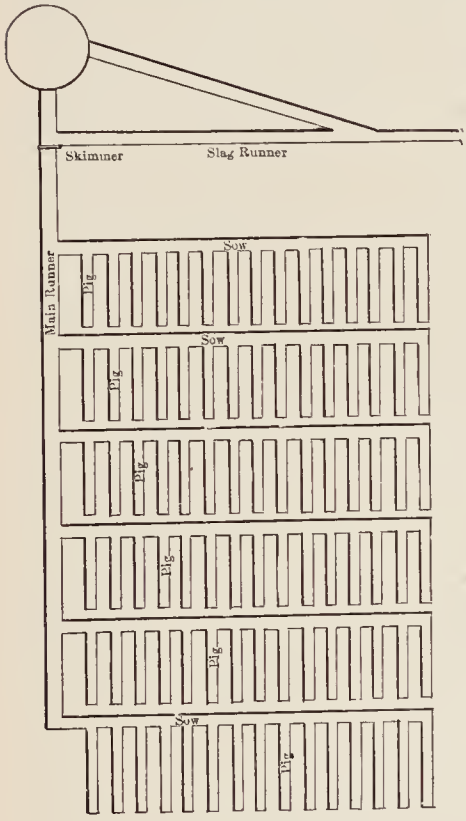


FIG. 20.—SAND-CASTING BED.

sary to cut a hole in the wall of the furnace and melt it out with a blow-pipe burning oil or gas, or with some other form of heat.

The "scaffolding" of a furnace and hanging of the charge is more liable to happen when large percentages of the earthy

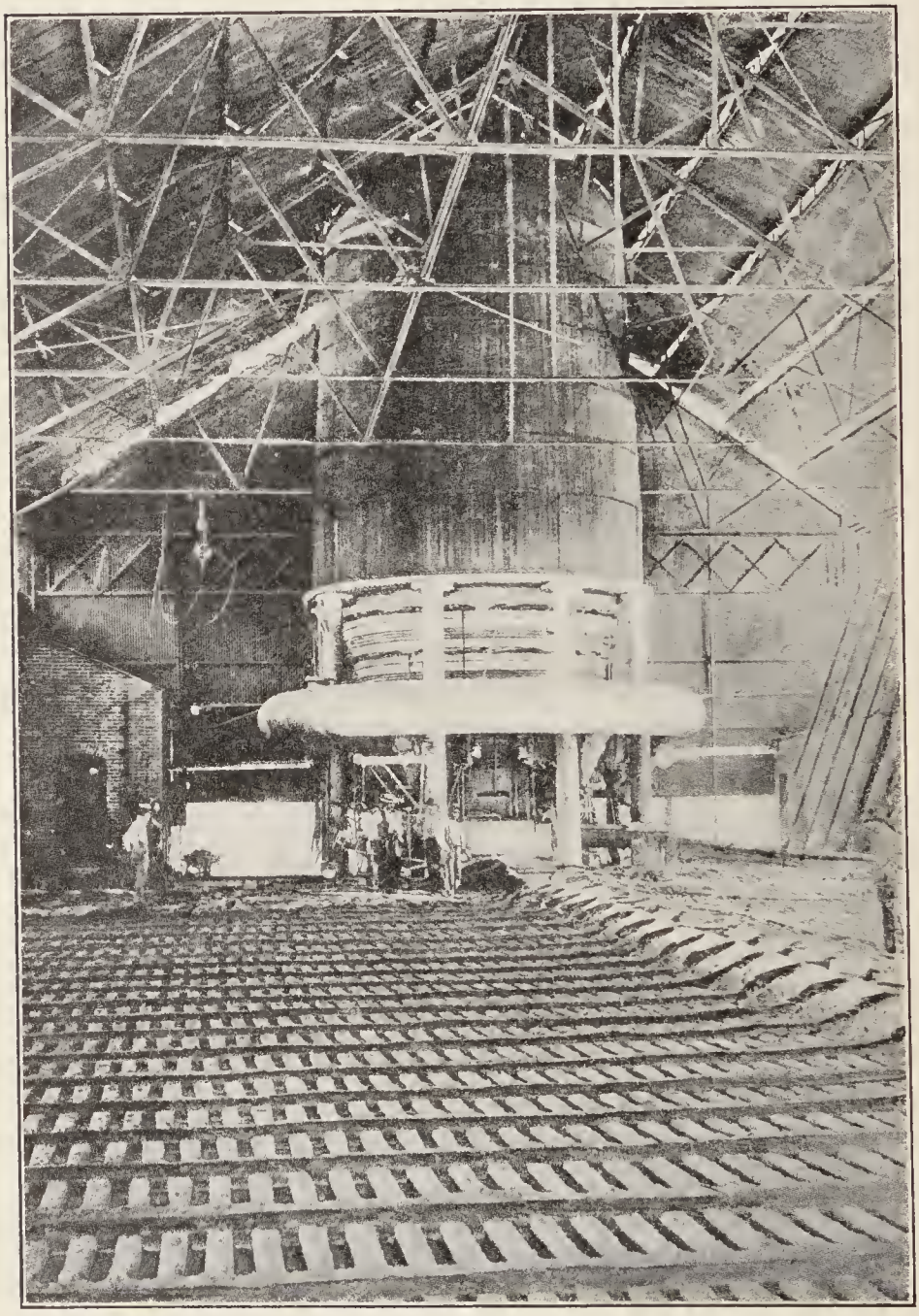


FIG. 21.—PIG BEDS.

Mesabi ores are used, and in this type of practice localized hanging and slips are not infrequent. When the slip is extensive in character and a large amount of material is suddenly precipitated into the hearth, the upward rush of gases resembles an explosion inside the furnace and may do damage to the charging apparatus and throw a part of the stock out of the top of the furnace. Some furnaces are provided with explosion doors, which fly open under pressure and relieve the strain; while the practice in other instances is to fasten everything down as tight as possible and prevent the rapid escape of the gases.

There is also a large amount of hanging due to the action of the blast in tending to drive the stock before it up into the stack of the furnace and thus compress it. This action is more liable to take place with fine ores.

Cooling of the charge also results in some cases in the freezing of material over the mouths of the tuyeres. The solid layer may sometimes be broken away with a bar, and the blow thus allowed to continue until more heat can be brought down into the hearth. Sometimes it is necessary to melt out the frozen material with a blow-pipe, and in extreme cases it may even be necessary to break through it with explosives.

Another difficulty sometimes met with is the freezing up of the metal in the lower part of the hearth, so that it is impossible to open the tap-hole. Then a new tap-hole must be made by boring through the front of the furnace at a higher level, from which the iron is drained, and then the heat gradually worked down until the whole hearth is melted out and normal conditions reëstablished. The bad work of a furnace is often cumulative in its effects, because irregularities in the smelting zone have an effect upon the top gases, which, in turn, derange the work of the stoves and hence impair the hot blast.

These irregularities in the smelting have a disturbing effect upon the character of the iron made, and the changes sometimes come suddenly and without warning. For instance, a sudden precipitation of cold material into the hearth will chill the smelting zone and cause the silicon in the iron to be low and the sulphur high. The same effect will be produced by the leakage of several gallons of water into the hearth through the burning out of a tuyere or the cooling-ring of one of the tuyeres.[1]

[1] In my early days at the blast furnace I was once informed by the assistant manager that, on one occasion, he tapped several tons of water from the tap-hole with the iron.

Dimensions of Blast Furnace.—The size of a modern blast furnace is limited by the conditions of its work; the hearth may not be much more than 15 ft. in diameter, else the blast from the tuyeres will not be distributed evenly to the center; the batter of the bosh walls cannot be much more nor less than a certain amount, because they must give support to the charge above them, and yet allow the solid coke to slip down; the height of bosh is limited, because its top must be practically the same as the top of the smelting zone—that is, no solid material except coke should descend into the bosh. These conditions therefore limit the diameter of the top of the bosh to not much more than 22 ft. From the bosh the stack walls must decrease in diameter upward in order that the descending charge, which swells in the reactions that take place from the throat downward, shall not become wedged in the stack; as the throat must have a sufficiently large diameter to properly charge the materials, this limits the height of the stack. Modern furnaces are therefore usually built about 90 ft. in height, and exceeding that limit has resulted in some cases in a decrease rather than an increase of fuel economy. Moreover, increasing the height of the furnace increases the blast pressure necessary much faster than the weight of the charge column so the height is soon reached at which the furnace can work only irregularly if at all.

Calculating a Blast-furnace Charge

This subject is of prime importance to young metallurgists, because the ability to calculate a charge is sometimes a cause of advancement, and the knowledge of the way to do so is not always obtainable from one's superior.

Assumptions.—Let us assume that we desire to produce a slag containing 55 per cent. lime, 15 per cent. alumina, and 30 per cent. silica, these proportions being determined by the experience of the manager, and that the materials from which the charge is to be made analyze according to Table III. Assume furthermore that the coke ash is equal to 10 per cent. of the coke, and that the iron we are going to make will contain about 1 per cent. silicon.

Whether he was himself deceived or whether he was merely trying to test me, I have never been able to decide; but the fact is worthy of mention in an elementary treatise to illustrate the character of the tales to which even the educated men around a plant will treat a novice.

TABLE III

Material	Per cent. CaO	Per cent. MgO	Per cent. Al_2O_3	Per cent. SiO_2	Per cent. Fe_2O_3	Per cent. Fe
Ore A	5	4	2	11	.....	60
Ore B	2	.....	12	16	.....	50
Coke ash	20	.....	18	50	.....	10
Limestone	46	4	2	4	.....	2

Silicon in the Iron.—This last assumption necessitates our allowing a corresponding amount of silica, because the silica reduced and absorbed by the iron will not be available for slag-making purposes. One per cent. of silicon is roughly equal to 2 per cent. of silica; we may therefore make the requisite allowance by subtracting from the silica in each material an amount equivalent to 2 per cent. of its iron content. Thus we begin to make up Table IV.

Magnesia.—In considering slags, magnesia is classified under the head of lime, thus obtaining column 2 in Table IV.

TABLE IV

Material	Per cent. CaO	Per cent. Al_2O_3	Per cent. SiO_2
Ore A	9	2	10
Ore B	2	12	15
Coke ash	20	18	50
Limestone	50	2	4

Self-fluxing of Materials.—It is evident that in so far as each of the materials in Table IV contains all the components of the slag, they will partially flux themselves. For example, the 2 per cent. of alumina in ore A will theoretically combine with 4 per cent. of the silica (2 per cent. $\times 30/15 = 4$ per cent.) and 7 per cent. of the lime (2 per cent. $\times 55/15 = 7.3$ per cent.) to make a slag of the desired proportions, leaving unfluxed percentages as per the first line of Table V. In the same manner we may use up all of the lime in ore B by uniting it with weights of

alumina and silica in proportion to the percentages of these components in the slag. Similar simplifications in the analyses of coke ash and limestone may then be calculated, and Table V will be completed.

TABLE V

Material	Per cent. CaO	Per cent. Al_2O_3	Per cent. SiO_2
Ore A	2		6
Ore B		11.5	14
Coke ash		13.0	39
Limestone	43		

Weight of Charge.—Let us assume that we are going to make one ton of pig iron for every ton of coke used in the charge, and that the coke will be put in in charges weighing 11,000 lb. each. This weight includes about 10 per cent. of moisture, dust, etc.,[1] so we calculate with it as if it weighed only 10,000 lb. Now let us determine how much ore will be put in each charge: The ores average 55 per cent. of iron; therefore, $\frac{10000 \text{ lb.}}{55 \text{ per cent.}} = 18{,}000$ lb., the amount of ore that must be in each charge, according to the assumption of this paragraph.

Adjusting the Alumina and Silica.—Next adjust the different materials so that the weight of alumina shall be 15/30 of the weight of silica. In the first rough approximation of this we may neglect the coke ash, because the weight of this ash is so small in relation to the other materials. Therefore only the two ores need be apportioned, and we quickly find by trying a few mixtures at random that 60 per cent. of ore A mixed with 40 per cent. of ore B will give the desired relation:[2] 60 per cent. $\times 6 + 40$ $\times$ per cent. $14 = 920$ parts of silica; 60 per cent. $\times\ 0 + 40$ per cent. $\times\ 11.5 = 460$ parts alumina; $460/920 = 15/30$. Now draw Table VI, and enter 10,800 lb. of ore A (= 60 per cent. of 18,000), 7200 lb. of ore B, 1000 lb. of coke ash (= 10 per cent. of 10,000), and the percentages from Table V. All the weights in

[1] This assumes that the breeze (or "braize") is removed after weighing the coke. If it is removed before, allow only 3 per cent. excess, which makes coke charges = 10,300 lb.

[2] Try first 50 per cent. of each, and we see that there is too much alumina; therefore try less than 50 per cent. of the ore having the most alumina, and correspondingly more of the other, and we have it.

this table may then be filled in except those of the limestone and total CaO.

To obtain the total number of pounds of lime:

Al_2O_3: 958 $\times \frac{55}{15} = 3513$ lb.
SiO_2: 2046 $\times \frac{55}{30} = 3751$ lb.
Average of 3515 and 3751 is 3632.

TABLE VI

Material		CaO		Al_2O_3		SiO_2	
	Weight	Per Cent.	Lb.	Per Cent.	Lb.	Per Cent.	Lb.
Ore A	10,800	2	216			6	648
Ore B	7,200			11.5	828	14	1008
Coke ash	1,000			13.0	130	39	390
	C		B				
Limestone	7,940	43	3416				
			A				
Total lb			3632		958		2046

Adjusting for Lime.—It is now only necessary to determine the amount of total lime that shall bear the correct relation to the alumina and silica calculated. This we do by means of the method shown in the figures above Table VI. We enter this in the square "A" of Table VI. The figures at the square "B" are then obtained (3632 − 216 = 3416), and thence the weight of limestone to be used —(3416 ÷ 43 per cent. = 7940).[1]

Checking the Calculations.—We now check up all the calculations by making up Table VII, in which we go back to the original percentages found by chemical analysis and given in Table III. In making up this final table, however, we use our experience in making slag calculations and estimate slight changes: For ex-

[1] In practice this is often much simplified by taking the Al_2O_3 simply as fixed, within wide limits, and figuring merely the ratio of CaO and MgO to SiO_2; disregard Al_2O_3, unless it is abnormally high, and therefore bad for physical reasons. If a constant limestone is used all such calculations are much simplified by figuring the net CaO and MgO in the stone after the SiO_2 in the stone is satisfied.

If a given ratio of CaO + MgO to SiO_2 be desired it is only necessary to add up the SiO_2 in ore and fuel, multiply by the desired ratio and divide by the efficiency of the stone. The net SiO_2 in the ores should be taken, that is, the SiO_2 fluxed by the bases in the ore should be deducted.

ample, Table VI shows us that the alumina comes a little low in relation to silica; therefore we increase ore B, say, by 400 lb. and decrease ore A correspondingly. But ore A is high in lime; therefore we use a little more limestone to offset this reduction.

TABLE VII

Material		$CaO+MgO$		Al_2O_3		SiO_2		Fe	
	Weight	Per cent.	Lb.	Per cent.	Lb.	Per cent.	Lb.	Per cent.	Lb.
Ore A.....	10400	9	936	2	208	11	1144	60	6240
Ore B.....	7600	2	152	12	912	16	1216	50	3800
Coke ash...	1000	20	200	18	180	50	500	10	100
Limestone..	8200	50	4100	2	164	4	328	2	164
Total weights.....			5388		1464		3188		10,304
							−206 (=2% 10, × 304)		
			=54.8 per cent.		=14.9 per cent.		2982 = 30.3 per cent.		

These figures are much closer to those desired than the limit of accuracy in furnace operation. The chief difference is that we are making a little more iron with 10,000 lb. of coke than we intended. If any change seems necessary it is then well to reduce the weight of ore A to 10,000, leaving everything else the same. This will lighten the burden and bring the calculated lime, alumina, and silica even closer to the desired figures.

Phosphorus and Manganese.—No account of the phosphorus has been taken in the calculation above. This is necessary sometimes. For example, if ore A happened to be very high in phosphorus we could not use so large a proportion of it. It would then be necessary either to secure another ore low in both phosphorus and alumina, or else to make a slag with less alumina. The same line of reasoning applies to manganese, but to less extent because the manganese in the iron can be controlled by the work of the furnace to a considerable extent, and in no event does more than two-thirds of that in the charge go into the iron.

III.

THE PURIFICATION OF PIG IRON

THE large amount of carbon in pig iron makes it both weak and brittle, so that it is unfit for most engineering purposes. It is used for castings that are to be subjected only to compression, or transverse or very slight tensile strains, as, for example, support-

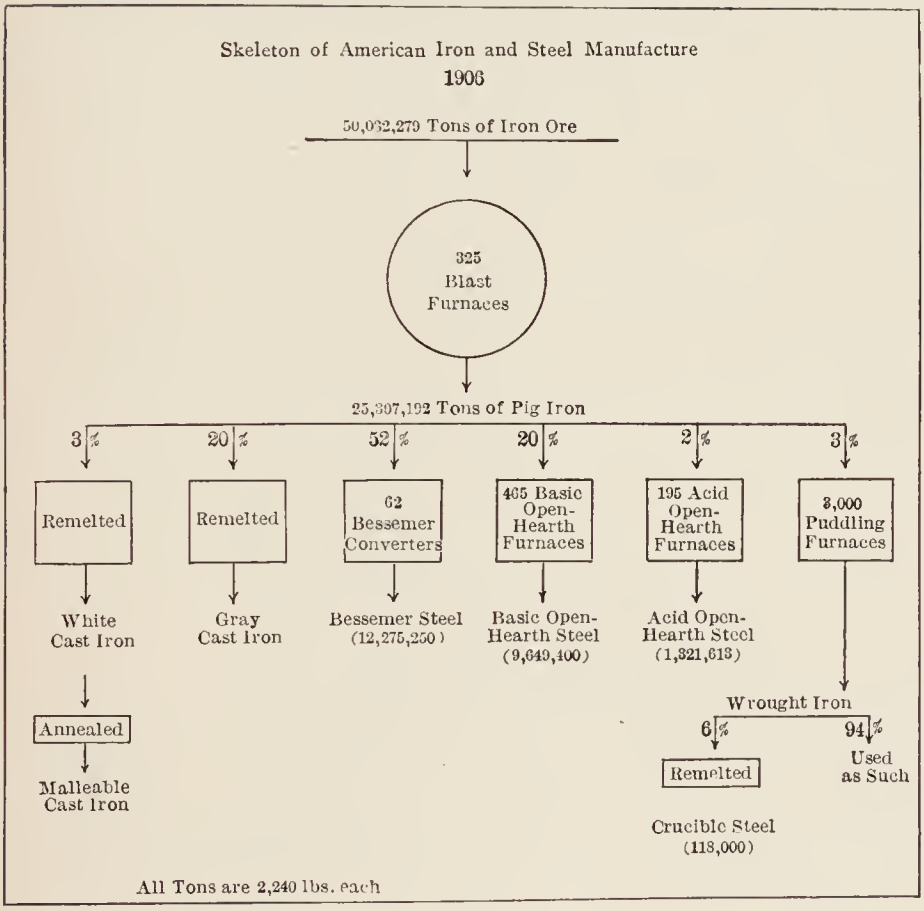


FIG. 25.

ing columns, engine bed-plates, railroad car wheels, water mains, etc., but the relatively increasing amount of steel used shows the preference of engineers for the stronger and more ductile material. To-day three-fourths of the pig iron made in the United States is subsequently purified by either the Bessemer, open-hearth, or

puddling process. Each of these will reduce the carbon to any desired point, while the silicon and manganese are eliminated as a necessary accompaniment of the reactions—indeed, we might almost say as a condition precedent to carbon reduction. Phosphorus and sulphur are reduced by the puddling process, and by a special form of open-hearth process known as "the basic open-hearth process."[1] The complete scheme of American iron and steel manufacture is given in Fig. 25.

Explanation of Fig. 25.—Practically all the iron ore mined is smelted in blast furnaces to produce pig iron. About 25 per cent. of the pig iron is used in the form of castings without purification, and 75 per cent. is purified and converted into another form. In all cases of purification the impurities are removed by oxidizing them, and we must again emphasize the rule that unoxidized elements dissolve in the metal, while those in the oxidized condition pass into the slag, or, if there is no slag, form a slag for and of themselves. In considering the Bessemer, open-hearth, and puddling processes then, we have to do with oxidizing conditions, whereas the opposite was the case in the blast furnace. The oxidation is effected by means of the oxygen of the air or that of iron ore, Fe_2O_3, or its equivalent, or of both air and oxide of iron.

There is not an exact relation between the amounts of pig iron used for the different purposes and the amounts of the resulting materials. In 1910 the following production was made:

PRODUCTION FOR 1910 (Long Tons)

	Pig Iron Used	Made
Malleable cast iron[2]	800,000*	1,000,000*
Gray cast iron	5,500,000*	6,750,000*
Bessemer steel	10,614,000	9,412,772
Basic open-hearth steel	9,084,520	15,392,357
Acid open-hearth steel	500,000	1,212,152
Wrought iron	800,000*	2,000,000*
Crucible steel		177,638
Electric steel		55,325

* Estimated.

[1] The basic Bessemer process is not in operation in America.

[2] It is true that the annealing process for malleable cast iron purifies the outer layers of the castings from carbon, and, if the castings are very thin, this purification may extend to the center; but this is not primarily a purification process and will be treated at length in another section.

The reason for this discrepancy is found in the scrap iron or steel mixed with the pig iron in the manufacture of gray-iron castings and open-hearth steel. Perhaps an average of 25 per cent. of old scrap will be mixed with 75 per cent. of new pig iron for making iron castings, and 50 per cent. or so of steel scrap will be mixed with 50 per cent. or so of pig iron in the basic open-hearth process, while wrought iron is often made by the piling and rerolling of old wrought-iron scrap.

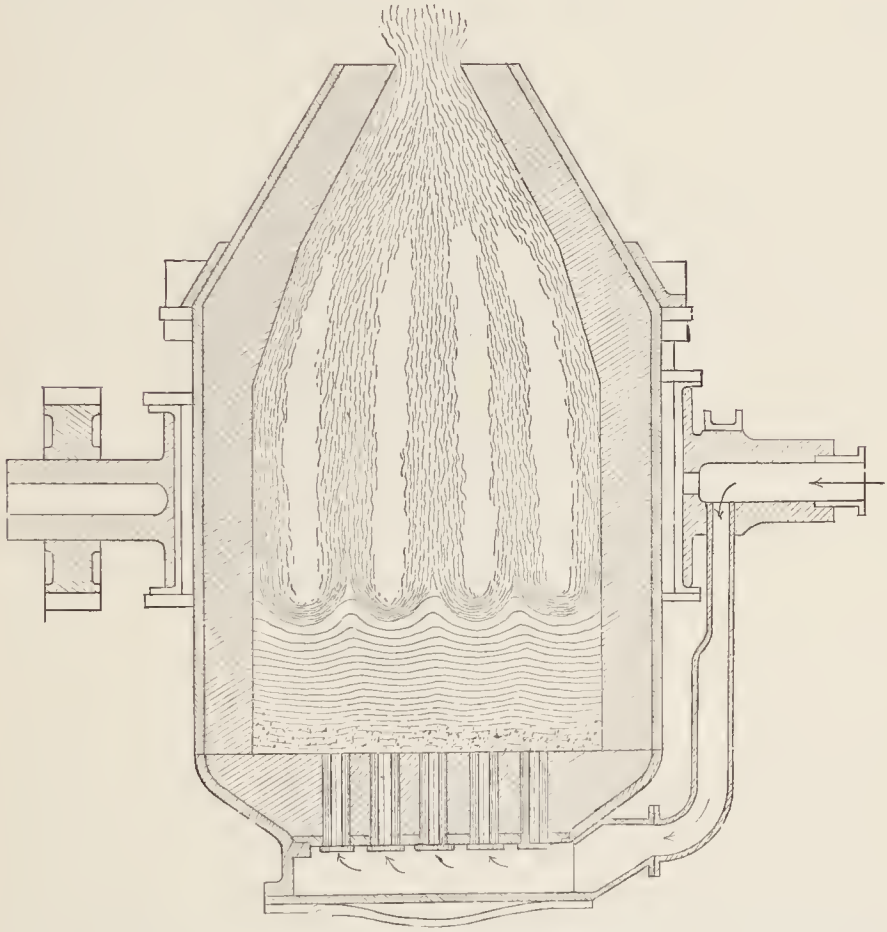


FIG. 26.—SECTION THROUGH BESSEMER CONVERTER WHILE BLOWING.

Bessemer Process.—In the Bessemer process, perhaps 15 tons of melted pig iron is poured into a hollow pear-shaped converter lined with silicious material. Through the molten material is then forced 30,000 cu. ft. of cold air per minute. In about four minutes the silicon and manganese are all oxidized by the oxygen of the air and have formed a slag. The carbon then begins to

oxidize to carbon monoxide, CO, and this boils up through the metal and pours out of the mouth of the vessel in a long brilliant flame. After another six minutes the flame shortens or "drops"; the operator knows that the carbon has been eliminated to the lowest practicable limit (say 0.04 per cent.) and the operation is stopped. So great has been the heat evolved by the oxidation of the impurities that the temperature is now higher than it was at the start, and we have a white-hot liquid mass of relatively pure metal. To this is added a carefully calculated amount of carbon to produce the desired degree of strength or hardness, or

FIG. 27.—BLOWHOLES OR GAS-BUBBLES IN STEEL.

both; also about 1.0 per cent. of manganese and 0.15 per cent. of silicon.[1] The manganese is added to remove from the bath the oxygen with which it has become charged during the operation and which would render the steel unfit for use. The silicon is added to get rid of the gases which are contained in the bath. After adding these materials, or "recarburizing," as it is called, the metal is poured into ingots, which are allowed to solidify and then rolled, while hot, into the desired size and form. The characteristics of the Bessemer process are: (*a*) Great rapidity of purification (say ten minutes per "heat"); (*b*) no extraneous fuel is used; and (*c*) the metal is not melted in the furnace where the purification takes place.

[1] In the case of making rail steel.

Acid Open-hearth Process.—The acid open-hearth furnace is heated by burning within it gas and air, each of which has been highly preheated before it enters the combustion chamber. A section of the furnace is shown in Fig. 28. The metal lies in a shallow pool on the long hearth, which is lined with silicious

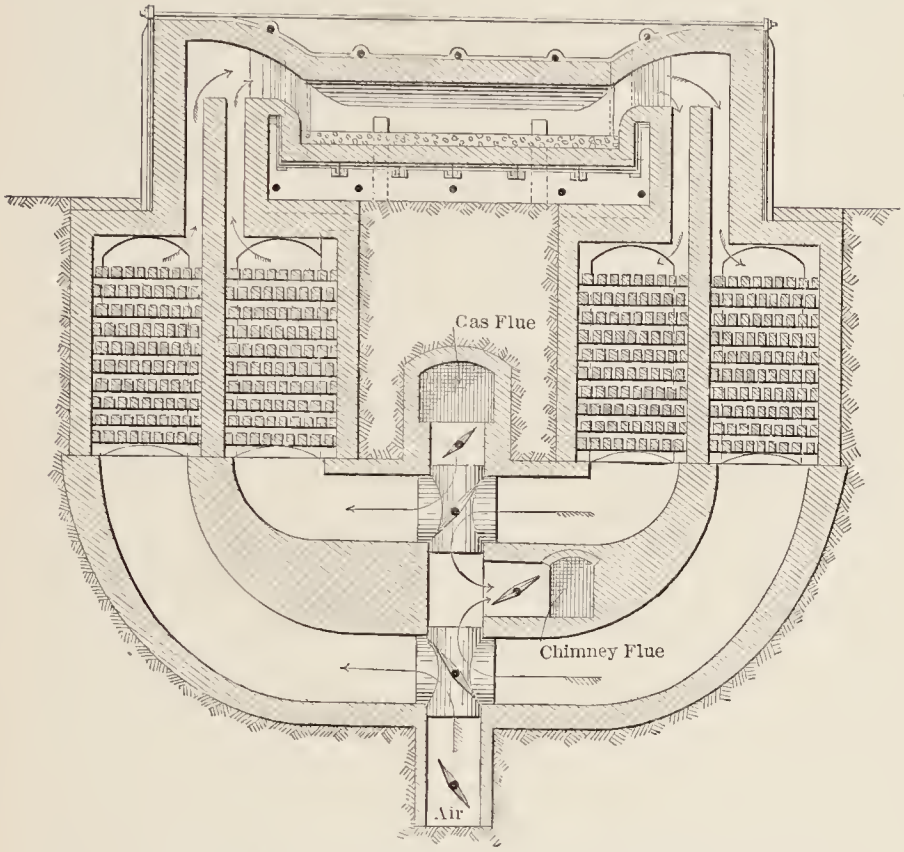


FIG. 28.—DIAGRAM OF REGENERATIVE OPEN-HEARTH FURNACE.

The four regenerative chambers below this furnace are filled with checkerwork of brick around which the gas and air may pass. Before the furnace is started these bricks are heated up by means of wood fires. The gas enters the furnace through the inner regenerative chamber on one side and the air enters through the outer one on the same side. They meet and unite, passing through the furnace and thence passing to the chimney through the two regenerative chambers at the opposite end. In this way the brickwork in the outgoing chambers is heated still hotter by the waste heat of the furnace. The current of gas, air, and products of combustion is changed every twenty minutes, whereby all four regenerators are always kept hot. The gas and air enter the furnace in a highly preheated condition and thus give a greater temperature of combustion, while the products of combustion go out to the chimney at a relatively low heat and thus fuel economy is promoted.

material, and is heated by radiation from the intense flame. The impurities are oxidized by the slag lying on top of the metal. This action is so slow, however, that the carbon in the pig iron takes a long time for combustion. The operation is therefore

hastened in two ways: (*a*) iron ore is added to the bath to produce the reaction.

$$Fe_2O_3 + 3C = 3CO + 2Fe,$$

and (*b*) the carbon is diluted by adding with the furnace charge large proportions of steel scrap, often as much as 75 or 90 per cent. It takes about 6 to 10 hours to purify a charge. The manganese and silicon go into the slag first; then the carbon boils off as a gas. When this has proceeded to the desired point we recarburize and cast the metal into ingots. The characteristics of the acid open-hearth process are: (*a*) A long time occupied in purification; (*b*) large charges are treated in the furnace (the modern practice is usually 15 to 100 tons to a furnace); (*c*) at least a part of the charge is melted in the purification furnace; and (*d*) the furnace is heated with preheated gas and air.

Basic Open-hearth Process.—The basic open-hearth process is similar to the acid open-hearth process, with the difference that we add to the bath a sufficient amount of lime to form a very basic slag. This slag will dissolve all the phosphorus that is oxidized, which an acid slag will not do.[1] The characteristics of the basic open-hearth process are the same as those of the acid open-hearth, with the addition of: (*e*) Lime is added to produce a basic slag; (*f*) the hearth is lined with basic, instead of silicious, material, in order that it may not be eaten away by this slag; and (*g*) impure iron and scrap may be used, because phosphorus and, to a limited extent, sulphur can be removed in the operation.

Puddling Process.—Almost all the wrought iron today is made by the puddling process, invented by Henry Cort about 1780, with certain valuable improvements made by Joseph Hall fifty years later. In this process the pig iron is melted in a reverberatory furnace the hearth of which is lined with oxide of iron. During the melting there is an elimination of silicon and manganese and the formation of a slag which automatically adjusts itself to a very high content of iron oxide by absorption from the lining. After melting, the heat is reduced and a reaction set up between the iron oxide of the slag and the remaining silicon, manganese, carbon, phosphorus, and sulphur of the bath, whereby the impurities are oxidized and all removed to a greater or less extent. The slag, because of its basicity (by iron oxide), will

[1] We can oxidize the phosphorus in any of these processes, but in the acid Bessemer and the acid open-hearth furnaces the highly silicious slag rejects the phosphorus, and it is immediately deoxidized again and returns to the iron.

retain all the phosphorus oxidized, and therefore the greater part of this element may be removed. The oxidation of all the impurities is produced chiefly by the iron oxide in the slag and the lining of the furnace, although it is probable that excess oxygen in the furnace gases assists, the slag by acting as a carrier of oxygen from it to the impurities.

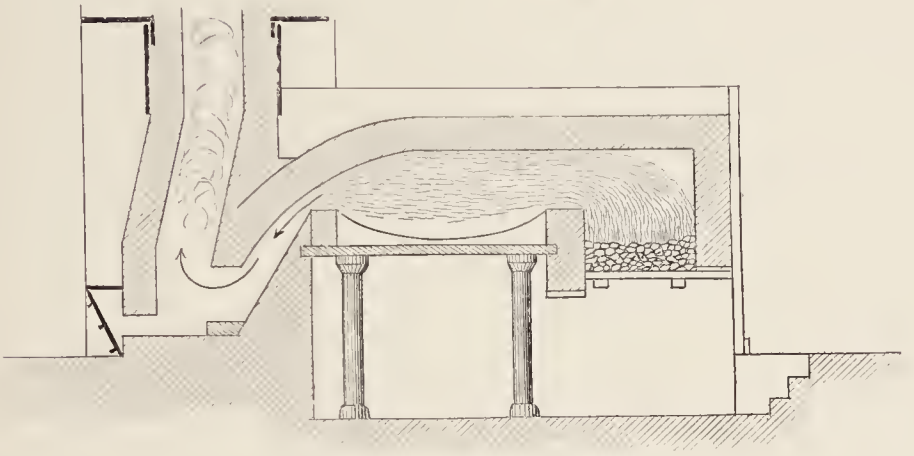


FIG. 29.—PUDDLING FURNACE.

The purification finally reaches that stage at which the utmost heat of the furnace is not sufficient to keep the charge molten, because iron, like almost every other metal, melts at a higher temperature the purer it is. The metal therefore "comes to nature," as it is called, that is to say, it assumes a pasty state.

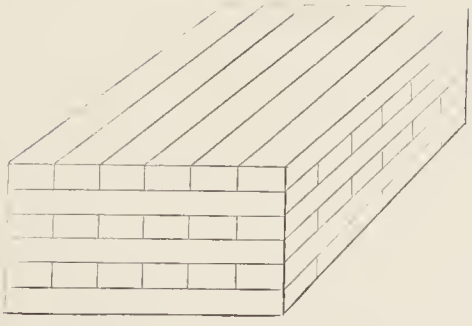


FIG. 30.—METHOD OF PILING MUCK BAR.

The iron is rolled up into several balls, weighing 125 to 180 lb. apiece, which are removed from the furnace, dripping with slag, and carried over to an apparatus, where they are squeezed into a much smaller size and a large amount of slag ejected from them. The squeezed ball is then rolled between grooved rolls to a bar,

whereby the slag is still further reduced, so that the bar contains at the end usually about 1 or 2 per cent. This puddled bar, or "muck bar," is cut into strips and piled up, as shown in Fig. 30, into a bundle of bars which are bound together by wire, raised to a welding heat, and again rolled into a smaller size. This rolled material is then known as "merchant bar," and all wrought iron, except that which is to be used for manufacture into crucible steel, is treated in this way before sale. The effect of the further rolling is to eject more slag, and also to make a cross network of fibers, instead of a line of fibers all running in the same direction, i.e., lengthwise of the bar. The fibers are produced by the action in rolling of drawing out the slag into strings, long fibers of metal also being produced, each of which is surrounded by an envelope of slag.

Miscellaneous Purification Processes.

Bell-Krupp Process.—The late Sir I. Lowthian Bell devised a process in which liquid pig iron is violently stirred up with iron oxide, producing a slag which carries away in the course of from 7 to 10 minutes more than 90 per cent. of the silicon and phosphorus in the metal. As soon as carbon begins to burn the process is stopped, and therefore there is almost no reduction in this element. The operation is conducted on the revolving hearth of a mechanical puddling furnace, into which the melted iron is poured while the hearth is rotating at about 11 revolutions per minute. The temperature is lower than that of the open-hearth process, in order that the elimination of phosphorus may be rapid. (See p. 59 and 146.)

The purified metal is used to some extent in the manufacture of crucible steel. During recent years, when the low phosphorus ores of America have become more scarce and the price of Bessemer pig iron is consequently increased, the metal has been bought to a limited extent by foundrymen using the acid open-hearth process or the baby Bessemer process for the production of steel castings.

Finery Fire.—This furnace is known under various names, such as "refinery hearth," "running-out fire," "finery fire," etc. It consists of a shallow, rectangular hearth, surrounded on the sides by water-cooled, hollow blocks of iron about 3 to 3 1/2 ft. long by 2 ft. wide and 24 to 30 in. deep. In and above this hearth is built a

fire of coke upon which is placed 500 or 600 lb. of pig iron. The coke is burned by a blast at 2 to 3 lb. pressure from 2 to 3 tuyeres on each side, and the pig iron gradually melts and sinks below it. When this takes place, more coke and pig iron is placed upon the top, and the operation repeated. A bath of pig iron forms in the hearth, and upon this the blast from the tuyeres impinges. This oxidizes the silicon in the metal, and also a large amount of iron, phosphorus, and sulphur. A slag high in iron oxide, and therefore very basic, is formed. As the temperature is low, phosphorus is eliminated without burning much carbon, and the result is the production of a purified iron still high in the latter element.

It takes about two hours to perform this purification, and then the metal is tapped out from the tap-hole in the front. It usually runs into a long, shallow trough, whence the name "running-out fire"; but sometimes the refined metal is not allowed to cool, but is run directly into the furnace in which the purification is to be completed. The consumption of coke in this first furnace is about one-eighth of the metal produced, and the loss from 5 to 20 per cent., depending upon the purity of the iron treated.

The running-out fire is frequently used in connection with the charcoal finery, known as the "knobbling fire," to produce knobbled charcoal-iron, which is employed especially for boiler tubes and to a less extent for boiler plate, wire, rivets, etc. Running-out fires for this purpose are, however, often known as "melting fineries," because in them the pig iron is melted before it goes to the knobbling fire.

Melting Finery.—In the melting finery there are usually two tuyeres in the back, and the melted metal, after an operation similar to that described above, is run directly into two charcoal fineries.

Charcoal Fineries.—The charcoal fineries, or "knobbling fires," are similar in general to Fig. 31, but have only one tuyere, situated in the back. They take a charge of 250 lb. apiece. During the transfer from the melting finery the slag is separated from the metal as well as possible, but some gets into the charcoal fineries. It is allowed to solidify and then is removed. Upon the metal is now charged some damp charcoal. The cold blast is turned on and the metal constantly agitated and raised up from the bottom so as to bring it in contact with the blast. Charcoal is added from time to time and is kept damp to avoid loss, and the slag is removed at intervals, but there must always

be a layer of slag between the metal and charcoal. As the metal comes to nature, it is pressed together with the pointed bar, like a crowbar, which is used for the agitation and raising. At the end of about an hour and a half, the ball is withdrawn and hammered. The cinder from the knobbling fire is usually charged into the melting finery.

The great advantages of the knobbled iron as compared to puddled iron are its softness and relative freedom from slag.

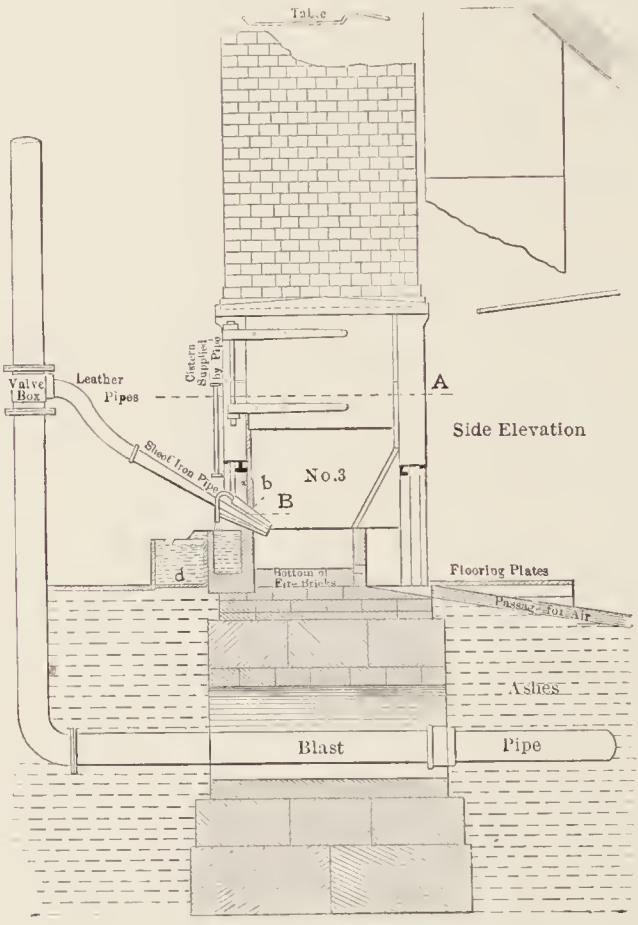


FIG. 31.—MELTING FINERY.

Also it is often lower in phosphorus and sulphur. Tubes made of this material may be flanged out very extensively without showing any cracks, and rivets will flow easily when hammered cold.

The Lancashire Process.—In the Lancashire process, which some believe is a decendant in Sweden of the purification in the

two fires last described, the same operations are performed in one hearth, which is made of iron plates, sometimes cooled with water, with a tap-hole in the front. The process consists of three stages:

1. The melting down, which is somewhat similar to the operation in the running-out fire or melting finery.

2. A purification period, during which the metal is nearly purified and comes to nature.

3. A remelting above the tuyere for further purification.

In America, pig iron heated red-hot in the chamber *H-C* (Fig. 32), during the working of a previous charge, is placed between two layers of charcoal and a little above the level of the tuyere. It is quickly melted, the liquid drops being forced to trickle down through the blast and thus be exposed to strongly oxidizing conditions.

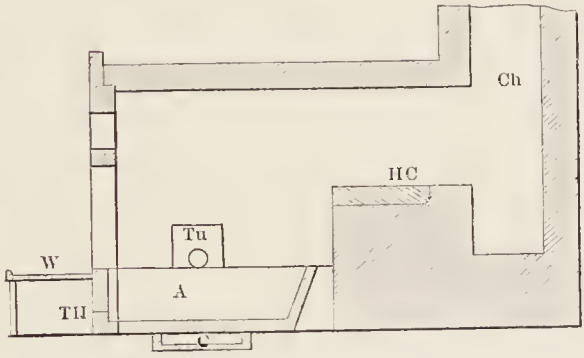


FIG. 32.—AMERICAN LANCASHIRE FURNACE. Tu = Tuyere. From Howe, "The Metallurgy of Steel."

The second period begins at the end of about 15 minutes, when the melted metal is all collected in the bottom. It becomes pasty in contact with the cold hearth, and is raised by a pointed bar and charcoal allowed to fall under it. Some slag at the same time is tapped off and some is mixed with the pasty lump, which produces a reaction between the two that assists in the purification. Toward the end of this period, which lasts 20 or 25 minutes, carbonic oxide comes off very rapidly, and when the metal becomes so stiff that great pressure is needed to raise it, and the slag has become thinner and whiter, the third period begins.

The metal is now broken into pieces and raised to its original position, the action of the first period being substantially repeated. During this period the workman is careful not to touch the mass collecting in the bottom of the hearth lest he mix slag with it. By the time about two-thirds of the metal is melted, some rich

iron oxide slag is added in order to keep enough in the bottom of the hearth to protect the metal from being carburized by the charcoal. When all the metal has melted and dropped down in front of the tuyere, the pasty ball is pried out of the hearth and hammered. The third period takes about 25 to 30 minutes.

Walloon Process.—In the Swedish Lancashire or Walloon process, the long pigs of metal are fed slowly down into the fire, so that it is not necessary to constantly pry them up with bars. The charges are smaller and the product is more liable to be

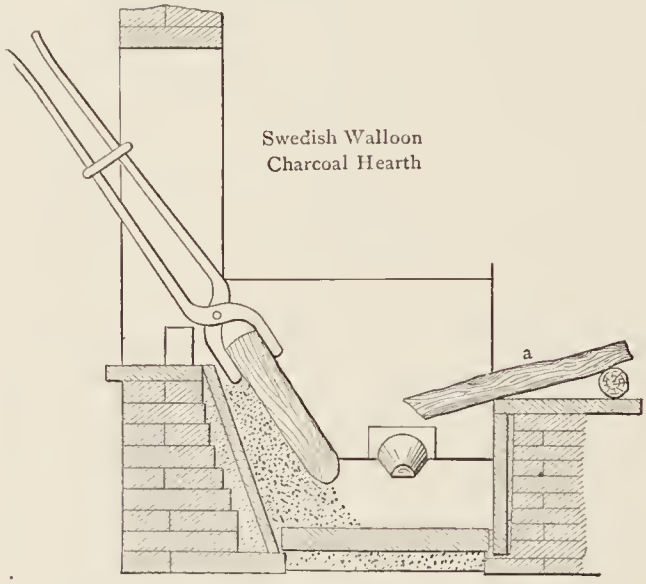


FIG. 33.—From Howe, "The Metallurgy of Steel."

heterogeneous, because the first melted metal is decarburized more than the last, and this heterogeneousness is not removed by the remelting. (See Fig. 33.)

The "Walloon process" is used in Sweden for making bar iron from the very pure pig iron reduced from Dannemora iron ore. This bar iron is used in Sheffield, England, for conversion into blister-steel, and some of the steelmakers pay a large price for it, in the belief that it has a certain intangible "body" not contained in wrought iron from any other process, and which makes a superior quality of steel. It is probable, however, that this body is wholly imaginary.

IV

THE MANUFACTURE OF WROUGHT IRON AND CRUCIBLE STEEL

The Manufacture of Wrought Iron

Pig Iron Used.—The pig iron employed is of the grade known as "forge iron" or "mill iron." In the United States we prefer to have this contain about 1 per cent. of silicon, because the higher the silicon the larger will be the amount of slag made, while if it is too low the iron will be oxidized excessively. Manganese is usually about 0.50 per cent., although it varies anywhere from 0.25 per cent. to over 1 per cent., depending on what the blast furnace puts in the pig. Phosphorus is preferred to be less than 1 per cent., and sulphur not more than 0.10 per cent., because neither of these elements is entirely eliminated during the process. A large amount of phosphorus in wrought iron is not, however, as objectionable as it is in steel, because the slag mechanically mingled with the wrought iron hinders it from being brittle under shock, which is the chief damage caused by phosphorus. Pig iron containing 2.50 per cent. and even 3 per cent. of phosphorus, and as much as 0.35 per cent. of sulphur, is sometimes used. The larger the amount of impurities the larger the loss of metal in the process, both because they are oxidized and lost and because, in the case of silicon, the oxidation increases the amount of slag made, which, in turn, increases the amount of iron slagged off.

Puddling Furnaces.—There are many different varieties of puddling furnace, varying in capacity from 300 to 1500 lb. and even more, but the commonest is probably the 500-lb. furnace, built either single or in pairs, back to back, the latter arrangement having the advantage of reducing loss of heat by radiation, which is always a very large factor. Puddling furnaces are heated by gas or bituminous coal. The commonest method is a deep bituminous-coal fire, giving a long flame, and with a large area of grate in relation to the area of the hearth in order that a high temperature may be maintained.

Fettling.—The hearth is lined or "fettled" with oxide of iron in the form of roll scale, or high-grade iron ore, or "bulldog," i.e., roasted puddle cinder, and this oxide, together with the

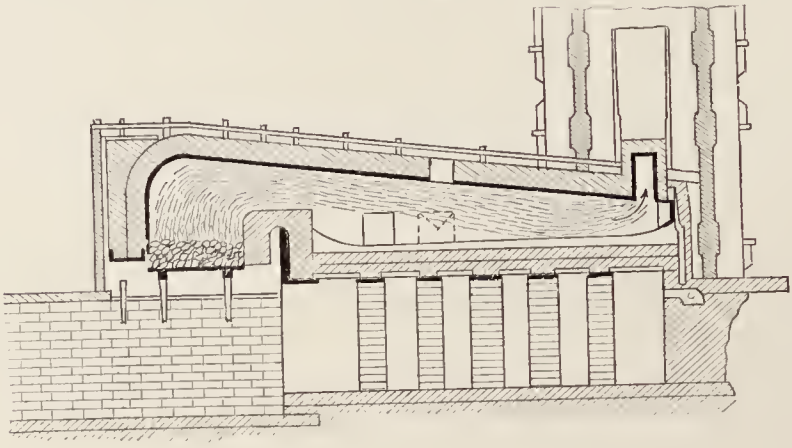


FIG. 34.—500-LB. PUDDLING FURNACE.

metal oxidized during the melting, supplies the base which automatically maintains a very basic slag and also serves as the principal oxidizing agent of the impurities. The fettling is repaired

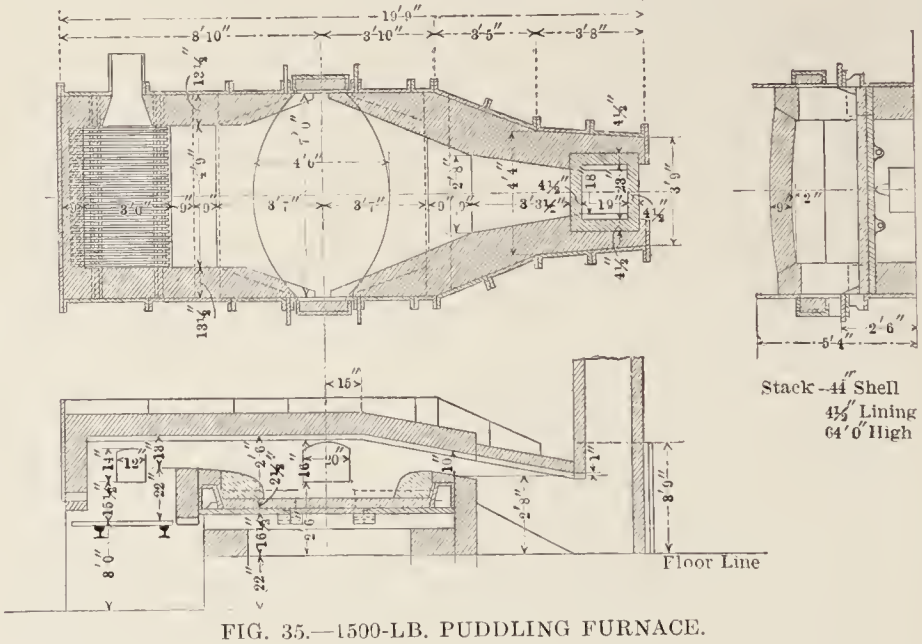


FIG. 35.—1500-LB. PUDDLING FURNACE.
(Two work doors)

between melts as often as is necessary, and suffers wear with each operation.

Puddling.—The pig iron is usually charged by hand through the

working doors of the furnace, and the puddler's assistant fires vigorously in order to melt it down as fast as possible, which usually takes about 30 to 35 minutes. As soon as melted, there follows a short stage of 7 to 10 minutes, during which iron oxide in the form of roll scale or very high-grade iron ore is added, in order to make a very basic slag, the charge being thoroughly mixed and cooled, for which purpose the damper is put on and

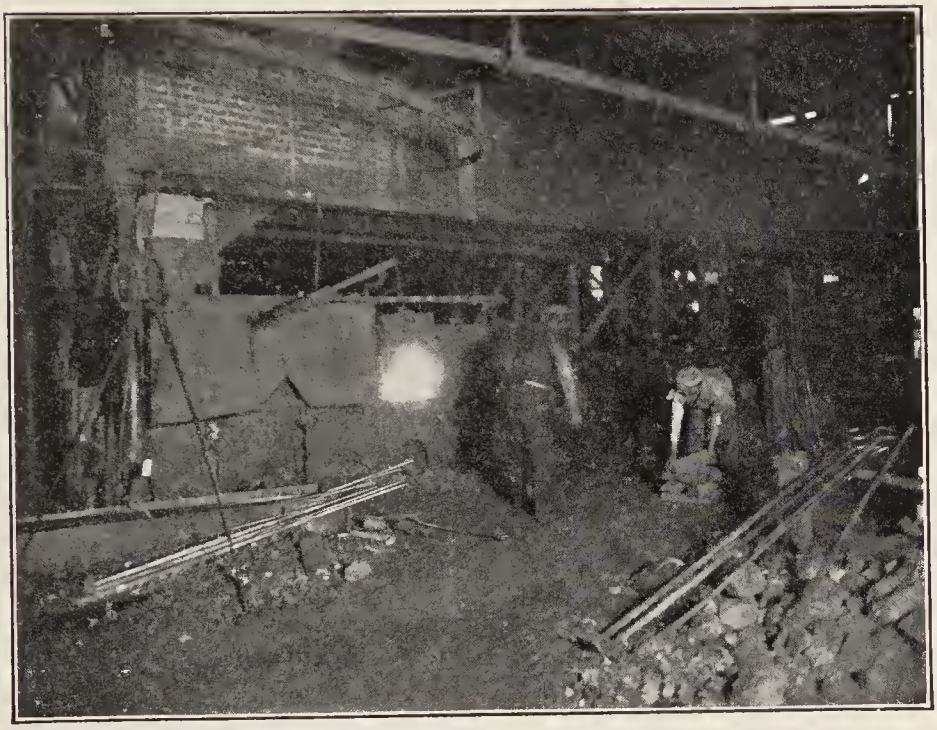


FIG. 36.—CHARGING THE PUDDLING FURNACE.

sometimes even water is thrown on to the bath. The object is to reduce the temperature to the point where the slag will commence to oxidize the impurities and especially the phosphorus and sulphur ahead of the carbon. At low temperatures, phosphorus oxidizes ahead of carbon; at higher temperatures, carbon in preference to phosphorus. See Table XI for slow removal of carbon at first. As soon as the carbon reaction is started, light flames begin to break through the covering of slag, produced by burning carbon monoxide:

1. $Fe_2O_3 + 3C = 3CO + 2Fe$;
2. $CO + O = CO_2$.

FIG. 37.—PUDDLING.

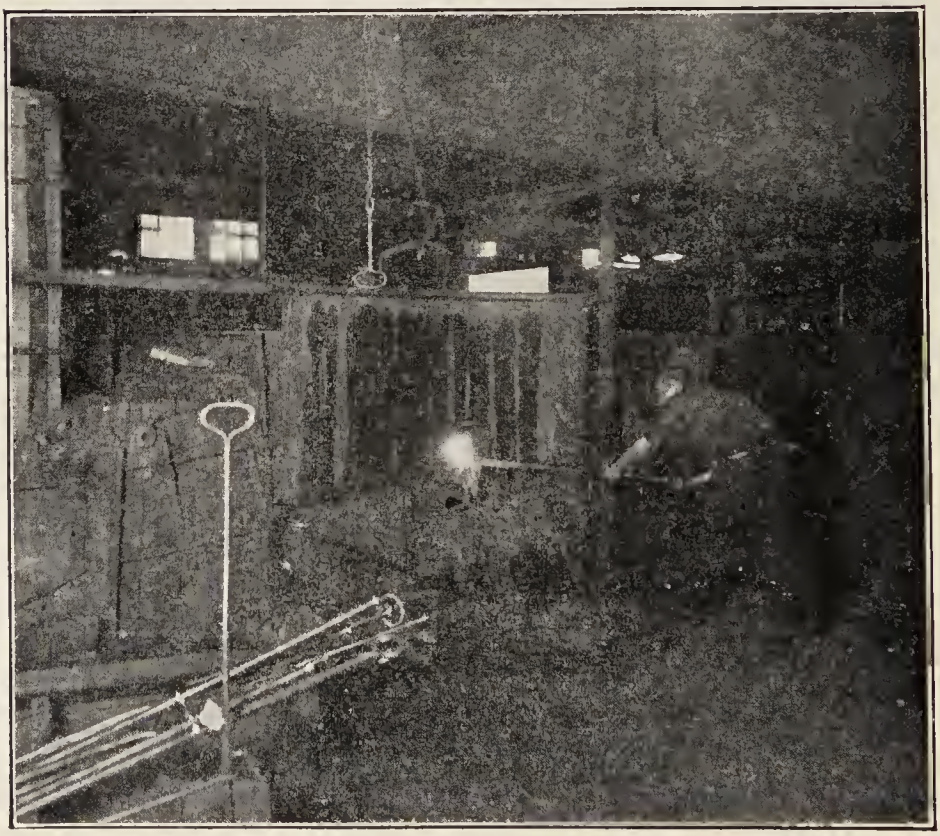


FIG. 38.—THE BOIL.
(A removable iron shield down which water flows protects the puddler from the heat.)

The slag must be very basic at this time lest the CO reduce phosphorus and sulphur and cause them to return to the metal.

As the carbon monoxide forms more and more abundantly, the charge is more violently agitated by its escape, and the "boil" is in progress. The formation of gas in its interior causes the charge to swell greatly, and it thus rises in the furnace and a large amount of slag pours out of the slag-hole and into a waiting buggy. About one-half of all the slag produced during the process is removed at this time. The boil continues from 20 to 25

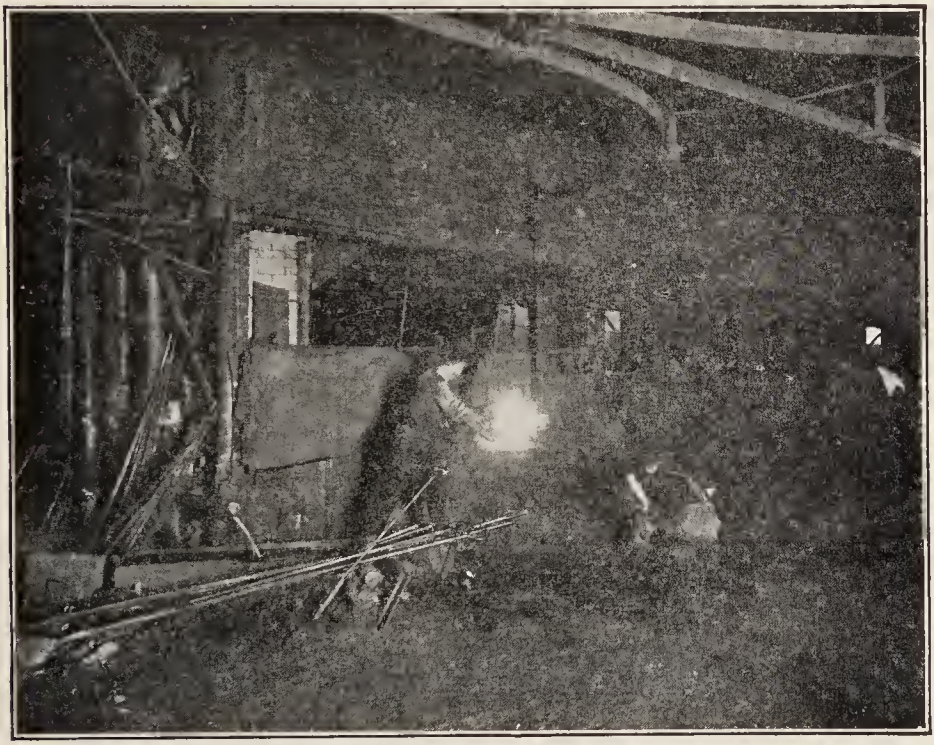


FIG. 39.—GETTING A HOLD OF THE BALL.

minutes, and during this time the puddler stirs or "rabbles" the charge vigorously with a long iron rabble, shaped like a hoe. Toward the end of the boil the metal begins to come to nature, and points of solid metal project through the cover of slag, while other pasty masses form on the bottom of the furnace. Both of these things must be corrected immediately by the puddler, lest (1) the iron that is exposed to the furnace gases become too much oxidized, (2) lest the iron sticking to the cold bottom become too much chilled, or (3) lest the charge be not uniform

FIG. 40.—TAKING THE BALL OUT.

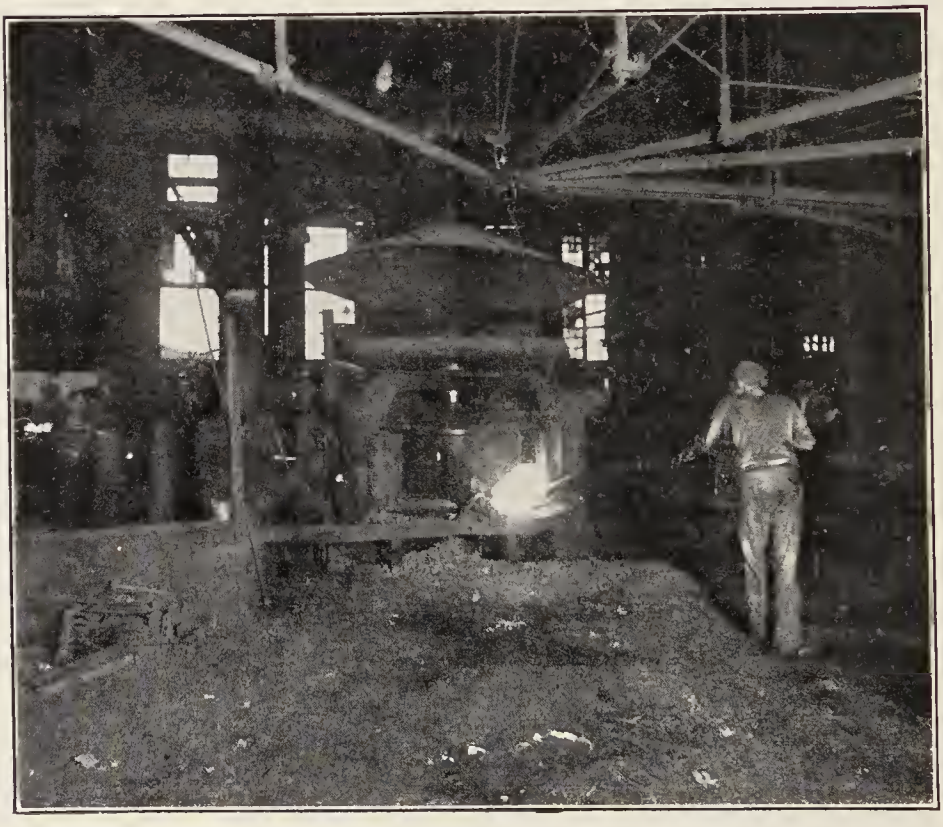


FIG. 41.—THE BALL ENTERING THE SQUEEZER.

in composition. Finally, all the charge comes to nature and the "balling" period begins and occupies about 15 to 20 minutes. During this period the bath is divided into three or four portions, which are each rolled up into a ball, consisting of a large number of particles partially welded together. The balls are rolled up near the fire-bridge in order, first, to protect them from direct contact with the flame, and second, to keep them as hot as possible until the puddler can draw them, so that the slag may be fluid and thus more easily squeezed out of the metal. The balls are then squeezed in turn, and the furnace hearth repaired for another charge. The total time between operations is usually from one hour and ten minutes to one hour and 40 minutes.

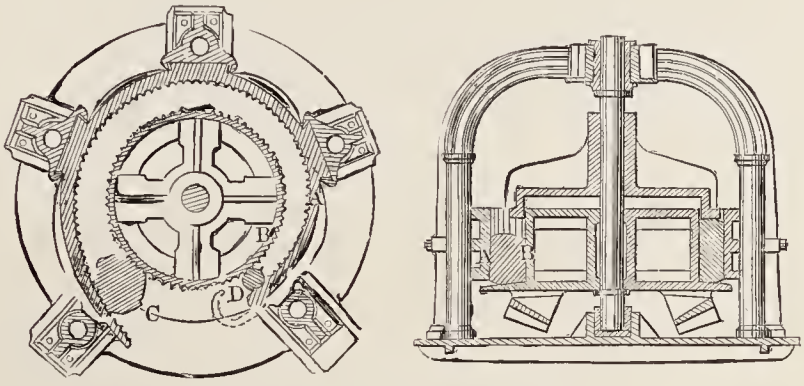


FIG. 42.—ROTARY SQUEEZER.

Squeezers.—A very common form of squeezer is that shown in Fig. 42, the distance between the inner and outer circle being greater on the entering side than on the outgoing side. As the inner circle revolves, the corrugations on the surface carry the ball around, giving it at the same time a movement of rotation. By the time the ball exits on the opposite side, it has been squeezed and kneaded sufficiently to get rid of a large amount of slag. In European countries the squeezer is rarely used and the ball is "shingled"—reduced under a hammer—to weld its particles together and force out the slag.

Chemistry of the Process.—The removal of the impurities during the puddling process are shown in Table XI, which is quoted because it records probably the first successful attempt ever made to study in this way the chemistry of an iron or steel process. A similar study is graphically represented in Fig. 43.

TABLE XI.—REMOVALS IN HAND PUDDLING

By Calvert and Johnson, *Phil. Mag.*, 1857

	Time after charging		C	Si	S	P
	Hrs.	Min.	Per cent.	Per cent.	Per cent.	Per cent.
Sample No. 1.....	0	0	2.275	2.720	0.301	0.645
Sample No. 2.....	0	40	2.726	0.915	.....	.....
Sample No. 3.....	1	00	2.905	0.197	.....	.....
Sample No. 4.....	1	5	2.444	0.194	.....	.....
Sample No. 5.....	1	20	2.305	0.182	.....	.....
Sample No. 6.....	1	35	1.647	0.183	.....	.....
Sample No. 7.....	1	40	1.206	0.163	.....	.....
Sample No. 8.....	1	45	0.963	0.163	.....	.....
Sample No. 9.....	1	50	0.772	0.168	.....	.....
Puddled bar.....			0.296	0.120	0.134	0.139

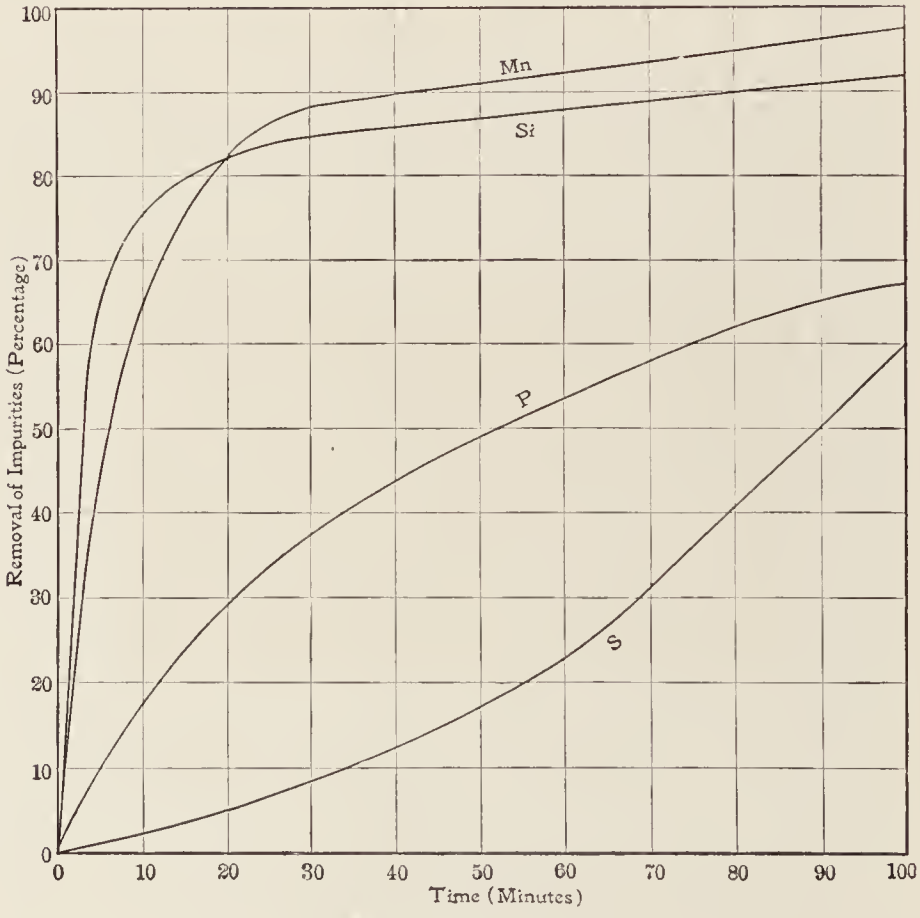


FIG. 43.—REMOVALS IN HAND PUDDLING.

During the melting-down stage, the silicon and manganese in the puddling charge are almost entirely eliminated, and these reactions are as complete as they will be by the end of the "clear-

FIG. 44.—PUDDLE ROLLS.

ing" stage which follows it. Much phosphorus and sulphur are also removed. The boil period is, of course, the period during which the carbon escapes, together with some phosphorus and sulphur which was not removed during the first two periods.

FIG. 45.—ROLLING PUDDLE BAR.

Fuel.—The temperature of the puddling process is as high as can be obtained in furnaces of this type without preheating the air.[1] The result is a very large waste of heat up the chimney,

[1] Indeed, in some cases the air is preheated by the regenerative process, although this is not the usual practice.

although sometimes economy in this respect is obtained by placing boilers, or else furnaces to heat metal for the rolls, where they will receive the waste heat of the puddling furnaces. The two greatest items of expense in the puddling process are the fuel used and the excessive labor, which, on account of the strength and endurance demanded, receives a high price. The amount of fuel burned per ton of iron produced will usually be about one ton of a soft bituminous coal, or a little more, although better figures than this are obtained in some cases.

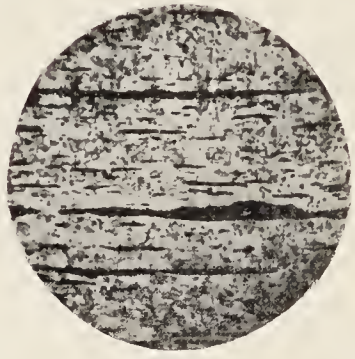


FIG. 46.—WROUGHT IRON SHOWING STRINGS OF SLAG MAGNIFIED 50 DIAMETERS.
(Unetched.)

Losses.—The loss in the puddling process usually averages from 4 to 6 per cent. of the weight of the metal charged. The following table gives a typical example of loss:

TABLE OF LOSSES IN HAND PUDDLING

	Percentage of loss
Silicon burned	1.00
Carbon burned	3.50
Sulphur burned	.20
Phosphorus burned	.50
Manganese burned	.30
Total	5.50
Iron reduced from oxide[1] = 1.00 per cent. gain.	
Net loss	4.50

Slag.—The slag which runs from the tap-hole during the boil is known as "boilings," while that tapped out at the end of the

[1] There is much iron oxidized and carried off in the slag, but there is also much reduced by impurities. The figure here given represents the excess of reduction over oxidation; in some cases it runs as high as 6 per cent. or more.

process is known as "tappings" or "tap-cinder." The characteristics of the boilings are that they contain a larger amount of phosphorus than the tappings, and also that globules of metallic iron are carried off in the violent agitation of the boil. An analysis of the two varieties, giving a mean composition from seven heats, is as follows:[1]

	Boilings	Tappings
Ferric oxide (Fe_2O_3)	6.94	12.90
Ferrous oxide (FeO)	62.61	64.62
Silica (SiO_2)	19.45	15.47
Phosphoric anhydride (P_2O_5)	6.32	3.91
Not determined (MnO, S, CaO, etc.)	4.68	3.10
	100.00	100.00
Total iron	53.55	59.29

The amount of slag will depend chiefly upon the amount of silicon in the pig iron. It will average in weight about one-half the weight of the charge, where the silicon is high, as in English practice (say 1.70 to 2 per cent.), and about one-quarter to one-third in American practice, where the silicon is about 1 per cent.

Mechanical Furnaces.—The labor in puddling is very severe on the men, and many attempts have been made to remedy this by mechanical furnaces which will work the charge without so much manual labor. Several forms of mechanical appliances and of mechanical furnaces have been invented, but without any permanent success. However, the mechanical furnace shown in Fig. 47, devised by James P. Roe, of Pottstown, Pa., has given some satisfactory results. It is suspended on trunnions, and the water-cooled bottom and sides are lined with magnesite brick. The oil and blast for combustion enter through the two trunnions and the products of combustion escape through a stack at each end, which meet above the top of the furnace and discharge into the atmosphere as shown. The furnace is made to oscillate 65° each way from the vertical, which keeps the slag and bath uniformly mixed and avoids the hand-rabbling of the ordinary

[1] Page 297 of Number 40.

puddling process. The whole charge, weighing about 4000 lb., is discharged in one ball by sliding it down the hearth of the furnace toward the end, and then out into a hydraulic squeezer of special design, in which it is compressed in three dimensions until it is a slab and ready for rolling.

Bundled Scrap.—In the United States a good deal of wrought iron is made every year by bundling scrap up into a pile roughly resembling Fig. 30. This is then tied up with wire, heated to a welding heat and rerolled into "puddle bar." This is generally an inferior grade of product.

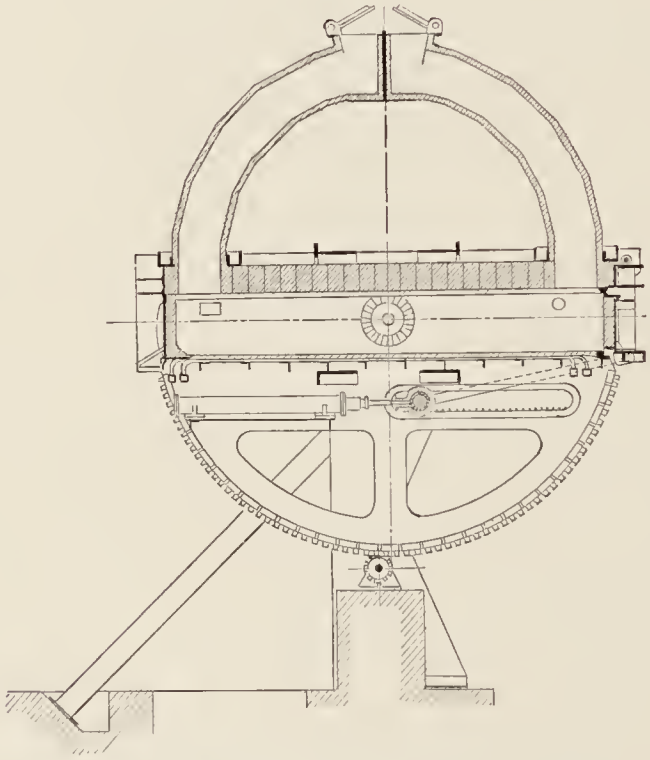


FIG. 47.—ROE MECHANICAL PUDDLING FURNACE.

The Carburization of Wrought Iron

Wrought iron is converted into steel by the operation of carburizing, or the adding of carbon to it. This is to-day accomplished in two ways: (1) By the cementation, or steel conversion, process, in which carbon is allowed to soak into red-hot steel in a manner like in nature to the absorption of ink by blotting-paper; and (2) by the crucible process, in which wrought iron is melted

in a crucible with carbon, or with iron containing carbon, e.g., cast iron, washed metal, etc.

Cementation Process.—We have already observed in describing the blast-furnace process that iron at a bright-red heat will absorb carbon very slowly. The action appears to be a traveling of solid carbon into the interior of solid iron, forming with it a chemical solution. When the steel is at a proper heat, the rate of travel is approximately 3/8 of an inch per 24 hours.

Steel Converting Furnace.—A section of the type of cementation-furnace used in Sheffield, England, is shown in Fig. 48. The superstructure, *e*, is a mere chimney for the purpose of carrying off the products of combustion from the fire at *c*, and for reducing loss of heat by radiation. The real furnace is the part underneath this superstructure or stack, and it has several small chimneys of its own. The two converting pots are shown underneath the points *a a*. In Sheffield they are built of stone and are 2 1/2 to 4 ft. wide and deep, and 8 to 15 ft. long. On the bottom of the pot is first placed a layer of charcoal in small pieces freed from dust. On this is laid a layer of the wrought-iron bars to be converted, which are 2 to 5 in. wide, 1/2 to 3/4 in. thick, and nearly as long as the pot. A little space is left (about 1/2 in.) between each pair of bars in order that they may be completely surrounded by the charcoal. On top of the layer of bars is then placed another layer of charcoal, and then a layer of bars, and so on until the pots are filled, each one containing from 10 to 30 tons of iron. The top of the pots is then luted air-tight and the fire lighted.

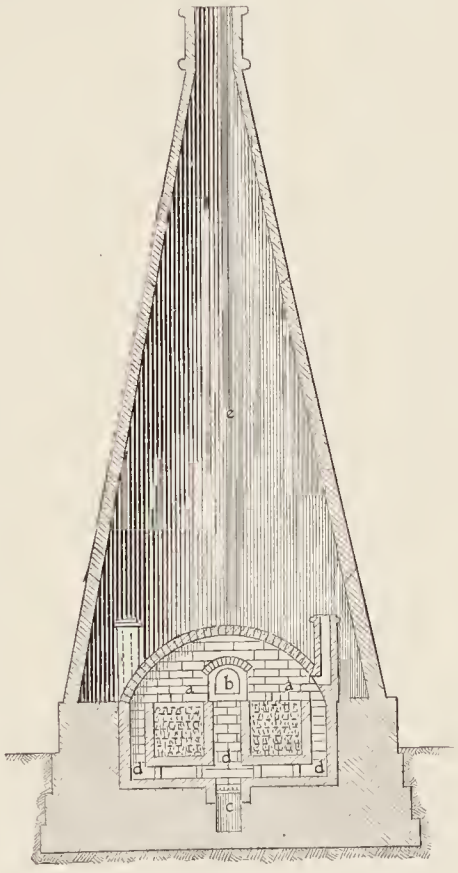


FIG. 48.—CEMENTATION FURNACE.

In about two days the temperature has reached a full red-heat

of say 650° to 700° C. (1200° to 1300° F.), and this is maintained from 7 to 11 days longer, depending upon the grade of steel to be made. The names of the different grades of steel made in Sheffield are as follows:

No. 1. Spring heat	0.50 per cent. carbon
No. 2. Country heat	0.60 per cent. carbon
No. 3. Single-shear heat	0.75 per cent. carbon
No. 4. Double-shear heat	1.00 per. cent carbon
No. 5. Steel-through heat	1.25 per cent. carbon
No. 6. Melting heat	1.50 per cent. carbon

The product is controlled by a series of trial bars which are so placed that, beginning about seven days from the full-red heat, they can be withdrawn from the furnace from time to time, broken, and examined. The appearance of the fracture tells the extent of the cementation. When the cementation has proceeded to the desired point, the fire is withdrawn and the furnace is allowed to cool for about a week, when the pots are opened and the bars withdrawn through the door *b*.

Blister-steel.—The product of the cementation process is known as "blister-steel" because its surface is covered with blisters, due to the formation of gas by a reaction between the carbon absorbed and the slag contained in the wrought iron:

$$C + FeO = CO + Fe.$$

The blister-steel has gained about 1 per cent. in weight over the wrought iron due to added carbon, and the appearance of the fracture is entirely different, as the broken surface now shows large bright crystals of cementite,—i.e, carbide of iron.

Shear-steel.—The bars of blister-steel are sometimes forged to a smaller size, piled up, and then the pile forged down again into a bar, which makes what is known as "single shear-steel." Single shear-steel may be again piled and forged into double shear-steel. It is now more common to melt the blister-steel in crucibles, which separates the metal from the slag it contains.

Crucible or Cast Steel.—The cementation process, on account of the length of time and the very large amount of fuel required, has now been largely superseded by the crucible process. In this process the wrought iron is cut up into small pieces and melted in covered crucibles, the desired amount of carbon being placed on top of the charge before the melting, together with any other alloying element desired, such as chromium, tungsten, manganese, etc.

Furnaces.—In Sheffield, England, coke-furnaces, or melting-holes, containing each two crucibles, are almost universally used, while in America gas-furnaces, containing about six crucibles each, are the common type. In the gas-furnace it is necessary

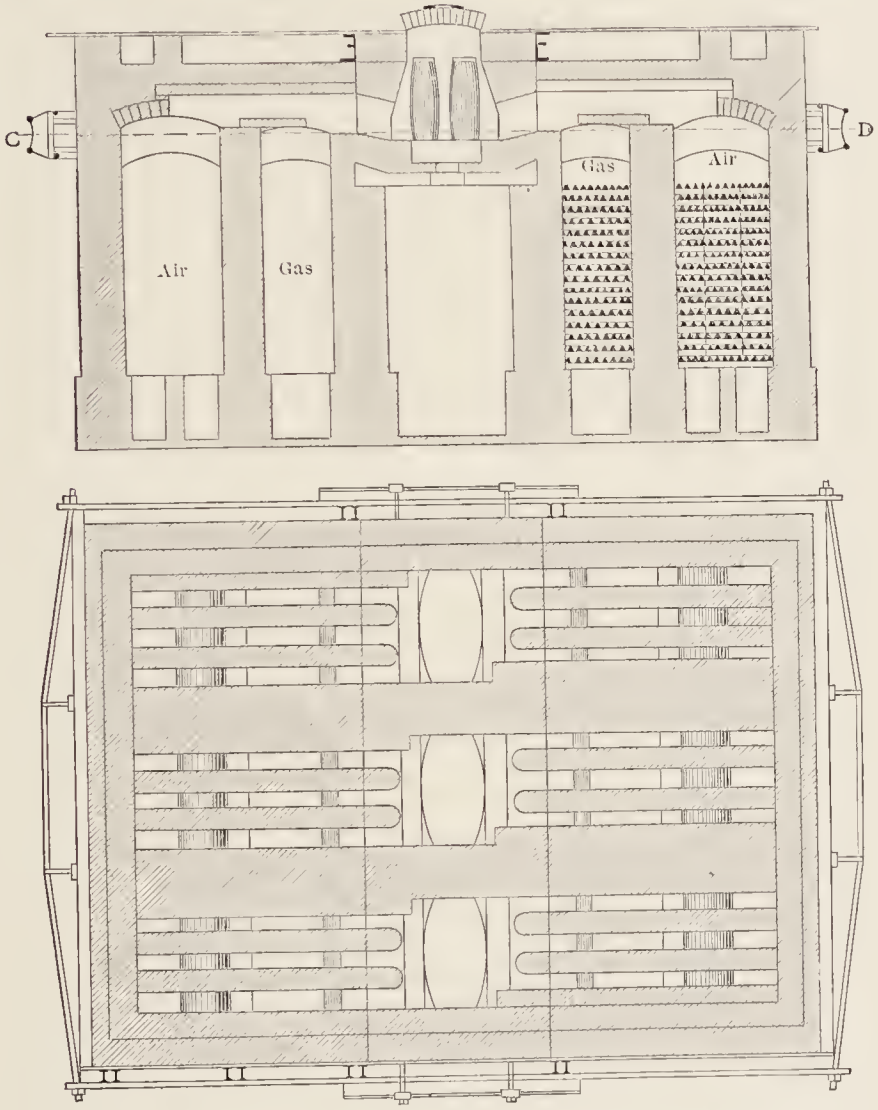


FIG. 49.—REGENERATIVE GAS CRUCIBLE FURNACE OR "MELTING-HOLE."

that the gas and air for combustion shall be preheated, in order that we may (1) obtain fuel economy and (2) reach the desired temperature for melting quickly.

Regenerative Furnace.—The operation of the regenerative furnace is shown in Fig. 49.[1]

[1] For description of the operation see page 49.

Crucibles.—In England, the crucibles are made of fire-clay. They are usually made by hand at the steel melting plants and are dried for one or two months, on a shelf next to the chimney of the melting-furnace. Before being used they are heated to redness in an annealing furnace and are then ready to receive a charge of 50 lb. of metal. The clay is deeply cut by the slag, and therefore the charge must be reduced to 44 lb. for the second melt and 38 lb. for the third, in order that the slag-line may be lower each time. After the third melt they are thrown away. The advantages of clay crucibles are that the first cost is lower, and

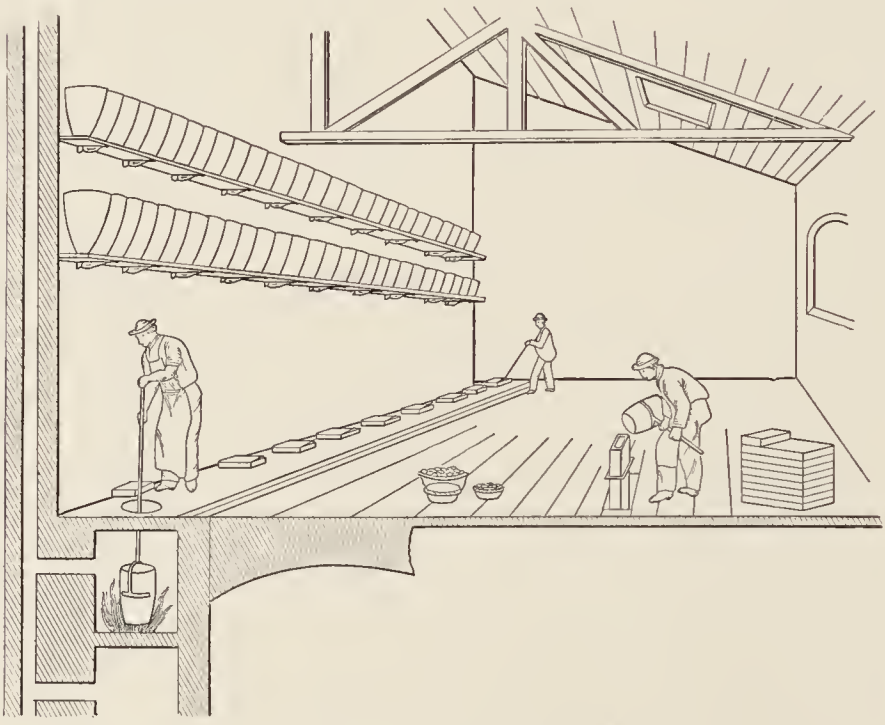


FIG. 50.—SECTION THROUGH SHEFFIELD MELTING HOUSE.

that they do not give up any carbon to the metal, so that the composition of the final product may be regulated with greater exactness and a lower carbon steel may be made, if desired.

In America, the crucibles are usually made of a mixture approximating 50 per cent. graphite and 50 per cent. fire-clay. They are made and tempered by factories outside of the steel-works and are received by the latter ready for use. They last about six heat, after which the bottom is sawed off and used for the top of a new crucible. They hold almost 100 lb. of metal, because at high heat, they are stronger than clay and can there-

fore stand greater strains. Grasping a crucible with the high-leverage tongs used and raising it from the furnace puts it under a severe strain.

Metal Used.—Although crucible steel is supposed to be made by the melting of pure wrought iron with charcoal, washed metal, ferromanganese and other "physic," it is not at all uncommon for the wrought iron to be diluted with varying amounts of cheaper scrap steel, which lowers the quality of the product. The pieces of iron are put into the crucible first, and on top of that is placed the charcoal or pig iron, ferromanganese or spiegeleisen, and various physics, such as salt, potassium ferrocyanide, oxide of manganese, etc. The purpose of these physics is not entirely clear. Probably the salt and oxide of manganese make a more fluid slag; the ferromanganese puts a little manganese in the steel; and the ferrocyanide may, perhaps, favor the absorption of carbon by the steel.

In some cases the material is charged directly into a hot crucible from the previous melt, but when graphite crucibles are used, these are sometimes allowed to cool, in order to be examined for cracks, because the breaking of a crucible in the furnace, allowing the liquid mass to flow out upon the floor, is very objectionable. There is a hole in the middle of the floor of the furnace, so that if such an accident happens the metal may run down into a pit underneath; and the floor is also covered with a few inches of coke-dust to absorb the metal in such a contingency.

FIG. 51.—STAGES IN CRUCIBLE STEEL MELTING.

Melting.—In the case of a gas-furnace the crucibles are placed in the furnace and the gas and air turned on. In the case of a coke-furnace, the crucibles are placed upon their fire-clay stands and the coke packed around them upon the fire left from the last melt. At the end of about an hour, the coke fire has burned down so low that it has to be poked down and more coke added. After another hour or so the coke fire requires further attention and at this time, care must be taken that no coke falls into the

crucible when the cover is off. The melting takes on the average from two to three hours in both cases, and the charge is examined by removing the crucible cover, to make sure that it is entirely molten.

Killing.—When the charge is entirely molten, it is kept in the furnace for one half to an hour longer in order that it may teem "dead," that is, pour quietly without the evolution of gas, and yield solid ingots. If the "killing" time is too long, the ingots will be solid, but the steel will be hard, brittle, and weak, probably as a result of the absorption of too much silicon from the walls of the crucibles. Graphite crucibles probably yield more silicon

FIG. 52.—POURING.

than clay crucibles. Just what takes place during the killing of steel is not definitely known. Some have suggested that the gas contained in the steel is eliminated from it during this time, but the alternate suggestion that the principal effect of the killing is to cause the steel to absorb silicon, becoming sound on this account, is the more generally accepted one. The amount of silicon in the final steel will vary greatly, but will average perhaps from 0.10 to 0.50 per cent.

Pulling.—When, in the judgment of the melter, the steel has been properly killed, the crucibles are removed from the fire by the puller-out, who straddles the top of the furnace and grasps the crucible with a pair of tongs, his legs and arms being swathed in wet cloths to protect him from the heat, and his eyes frequently being protected by heavy blue glasses. The puller-out then passes the crucible to the pourer, who pours it as shown in Fig.

52, the slag first being swabbed off with a ball of cold slag on the end of an iron rod. The total time of operations is 3 1/2 to 5 1/2 hours in England, and 3 1/2 to 4 hours in America.

Ingot Molds.—Ingots mold are shown in Fig. 53, and as a usual thing each mold has a capacity to take the charge from one crucible. The metal must be teemed into this with great care, so that the stream shall not touch the sides during pouring. In case a large ingot is to be poured, several crucibles are poured at once into the same mold, care being taken that the metal shall be liquid as long as the pouring continues., or else a "cold-shut" will result; that is, two parts of the ingot not fully melted together.

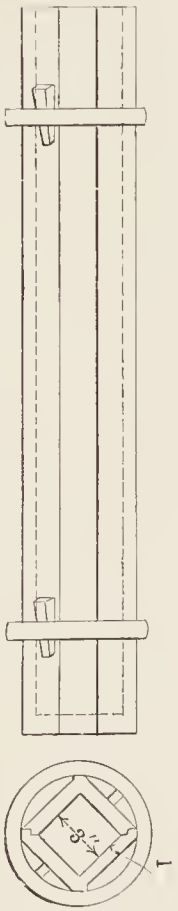


FIG. 53.—INGOT MOLD FOR CRUCIBLE STEEL. From Howe, "The Metallurgy of Steel."

Grading.—The composition of the final metal is a matter of some uncertainty, especially as regards the carbon and silicon. The former is more easily adjusted when clay crucibles are used, because the amount of carbon dissolved from a graphite crucible will depend to a large extent upon the time and temperature of the operation, etc. The ingots are therefore always graded after they have cooled, by breaking off the upper part of them, which contains the pipe and is therefore useless except when remelted, and examining the fracture with the eye. The skilled steel man can thus estimate the carbon within 0.10 per cent., and the ingots are put away in the pile with others of like analysis. At large American works, however, this grading by eye is always supplemented by chemical analysis.

Chemistry.—The chemistry of the crucible process is very simple, and consists principally in the elimination of the slag in the wrought iron and the absorption by the metal of carbon, silicon and manganese. There is also a very slight increase in sulphur, which perhaps comes from the pyrite in the clay or graphite, or from sulphurous gases which find their way under the cover of the crucible. Phosphorus also increases slightly, perhaps from the slag of the wrought iron.

Loss.—The loss is due to the elimination of the slag and to some slight oxidation of metal by oxygen inside the crucible.

It is counteracted to some extent by the absorption of carbon, silicon, and manganese, and will average slightly more than 2 per cent. in clay crucibles and somewhat less than 2 per cent. in graphite crucibles, the difference being doubtless due to less oxidation in the presence of the graphite.

Fuel.—In coke fires, the amount of fuel used will be three to four times the weight of steel produced. In gas-fired furnaces the amount of fuel used to make producer gas will be equal to, or slightly less in weight than, the amount of steel produced. The high cost in making crucible steel is due to the cost of crucibles, fuel, labor, and raw material.

FIG. 60.—A BESSEMER BLOW.

V

THE BESSEMER PROCESS

Pig Iron Used.—In the large American works, pig iron for the Bessemer process is preferred to have about 1 per cent. of silicon. Silicon is the chief slag producer and also the chief heat producer. To keep it at a low figure limits the amount of slag made, which limits one of the sources of iron loss. Furthermore, the lower the silicon the shorter will be the time of blow; but it is usually risky to allow it to fall below 1 per cent., or the blow will be cold, and it is only by very rapid working and permitting the least possible delay between operations, so that the converter and ladles are kept very hot, that we are able to get along with as little as this. The manganese is below 0.8 per cent. This also furnishes heat[1]; but it is now an expensive ingredient of pig iron, and also has the effect of making very liquid slags, which cause a good deal of slopping or "spitting" from the converter (i.e., ejection of the material by the blast), and also make the steel ingots dirty and spotted with oxide spots, due to slag carried over with the steel. Pig iron containing manganese 1.50 per cent. and silicon 1.00 to 0.90 per cent., gives a very "wet" slag, which follows the metal into the ladle and boils up through it, oxidizing the manganese in the steel:

$$(1)\ FeO + Mn = MnO + Fe.$$

The phosphorus and sulphur must be below 0.10 and 0.08 per cent., respectively, in order that the steel may be salable, as neither of these elements is reduced in the acid Bessemer process.

Mixer.—It takes about two blast furnaces to supply one converter with metal, so that a modern plant of two to four converters will be operated in conjunction with a large blast-furnace plant. The product of each of these furnaces, if not too different from the desired analysis, will be poured into a huge reservoir, or "mixer," capable of holding 150 to 500 tons, which is then used as a source of supply for the converters.

[1] Indeed, formerly, in the Swedish Bessemer practice, the pig iron contained 2 per cent. of manganese, and this element was relied upon as the chief source of heat, because silicon was necessarily low in the Swedish charcoal pig iron.

The mixer serves several very useful purposes: (1) It equalizes the irregularities of pig iron composition by mixing the product of several furnaces, and also brings the composition somewhat under the control of the metallurgist of the Bessemer plant, because he not only can pick and choose from the different furnaces, but he has a few large cupolas under his dominion in which he can melt iron of any desired analysis to pour into the mixer and help regulate its contents.

(2) Because of its large size, and the fact that it is continually in receipt of new fresh metal, the mixer can keep its contents

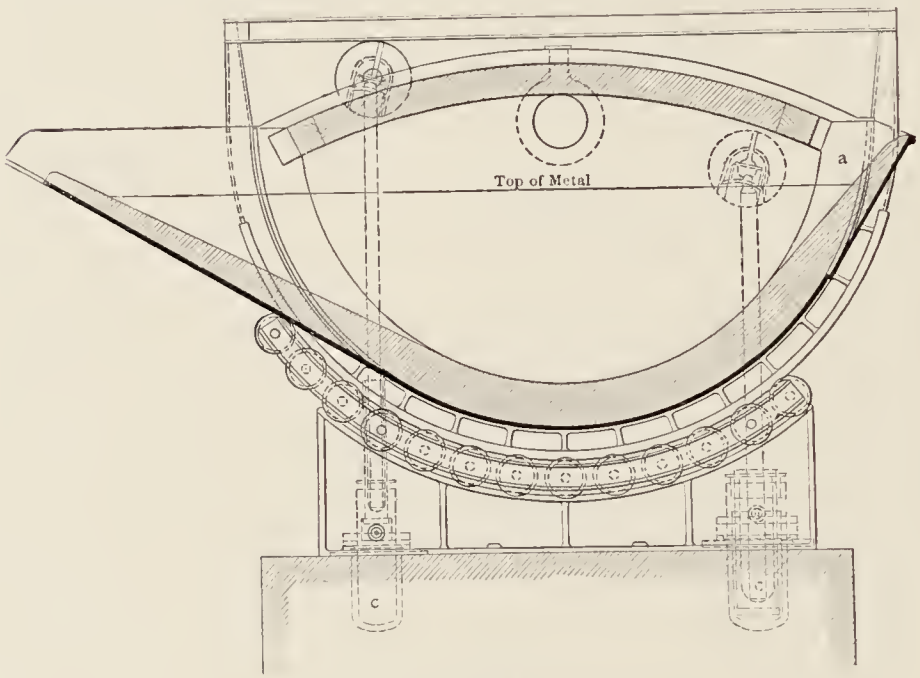


FIG. 61.—MIXER.

molten for an indefinite length of time, whereas a ladle containing 15 tons of pig iron would chill up in a very few hours. Mixers are supplied with blowpipes which can contribute a small amount of heat to the charge, but it is not often necessary to use them. Sometimes they are heated by gas and the regenerative process.

(3) The capacity of the mixer is so large that a delay either at the blast furnace or at the steel-works will not discommode it greatly, and thus each operation is independent of the other.

(4) Pig iron in the mixer suffers a slight loss in sulphur, because manganese sulphide forms and, not being very soluble in iron, slowly rises into the slag.

Construction of the Converter.—The construction and dimensions of the converter are shown in Figs. 62 and 63. It consists of a steel shell, riveted together and supported by two trunnions upon which it can be made to rotate. One of these trunnions is hollow, and serves as a wind-pipe to connect the blast from the blowing-engine with the wind-box at the bottom of the vessel. On the other trunnion is fastened a pinion, which engages with a

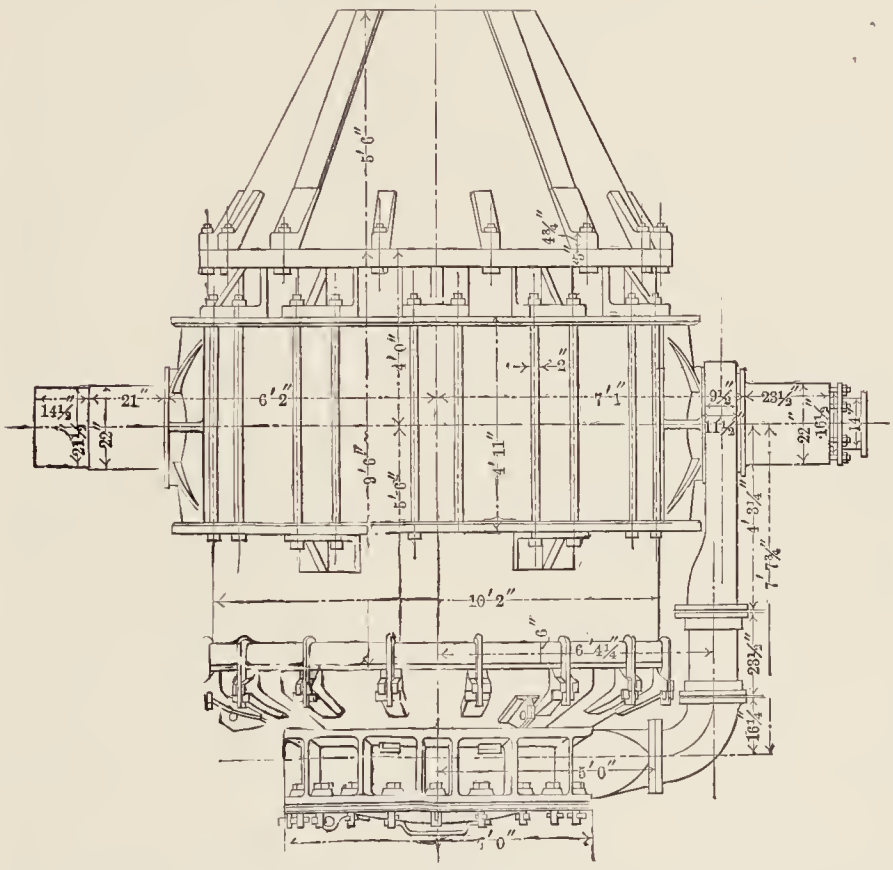


FIG. 62.—FIFTEEN-TON CONVERTER SHELL. From Howe, "The Metallurgy of Steel."

rack joined to a hydraulic piston and of such a length that its movement can rotate the converter through an angle of at least 270°. The lining of the bottom is pierced with about 250 half-inch holes, which connect the wind-box with the inside of the converter and serve for the passage of the blast. The shape of the converter is such that, when it is lying on its side, the metal will not cover any of these tuyere-holes. This is necessary, or the

blast could never be turned off without having molten metal run down into the wind-box. The converter may have either an eccentric or a concentric shape. The advantage of the eccentric shape is that less heat can escape from the nose; the advantage of the concentric shape is that the vessel may contain its charge when turned on either of the sides, or may receive and pour from either side.

Lining.—The lining is made of highly refractory acid material composed principally of silica. In England, a ganister rock is

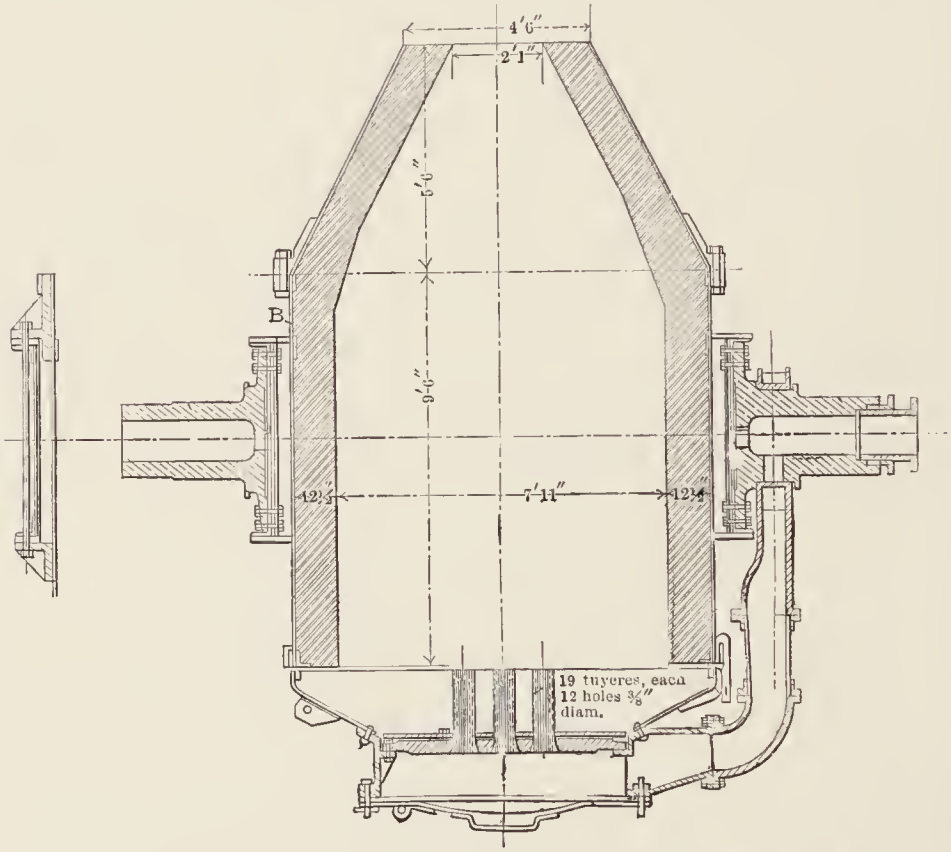


FIG. 63.—FIFTEEN-TON CONVERTER SECTION. From Howe, "The Metallurgy of Steel."

used, or sometimes the lining is rammed up around a pattern and is composed of silicious material held together by a small amount of fire-clay. In America, it consists usually of blocks of ganister or of mica-schist (a silicious rock consisting of pseudostrata, or laminæ, formed by tiny plates of mica) laid with a thin layer of refractory fire-clay between, and in such a manner that the edges

of the laminæ will be exposed to the wear to which it is subjected.[1] After a new lining is put in, it is carefully dried, and every Sunday afternoon, before the converter begins its operation for the week, a wood fire is kept in it for several hours in order to heat the lining to a red heat. Between the heats the lining is repaired, if necessary, with balls of silicious material and clay. On Sundays, and with an occasional lay-off for which one extra shell

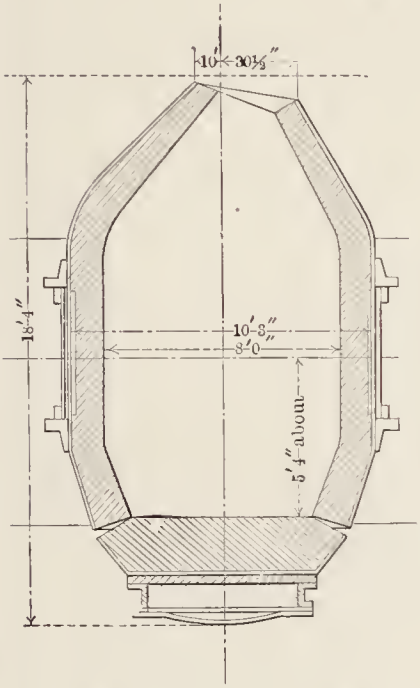


FIG. 64.—From Howe, "The Metallurgy of Steel."

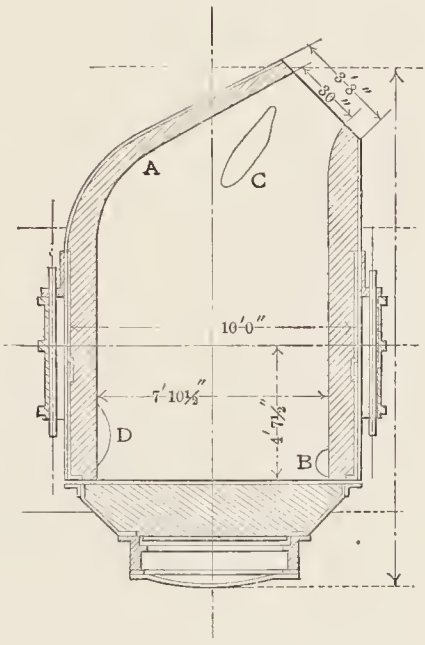


FIG. 65.—ECCENTRIC CONVERTER. From Howe, "The Metallurgy of Steel."

is provided, more extensive repairs are made, and in this way the lining is made to last several months—say 10,000 to 20,000 heats. The converter slags are always high in silica and corrode the lining only slightly. If, however, any uncombined oxide of iron comes in contact with it, it is attacked very rapidly. For this reason the mouths of the tuyeres are rapidly eaten away, and this part of the converter lasts only about 20 to 25 blows. The bottom is therefore fastened to the body with links and keys, so that it may be readily detached and replaced by a new one.

[1] If we represent the blocks of mica-schist by big books, and lay these books in a horizontal position with the edges of the leaves exposed, it will illustrate the method employed.

Indeed, in some works bottoms are changed with an average delay to the operation of only about 20 minutes for each replacement.

Bottoms.—The lining of the bottom is made by placing the tuyere-bricks (see Fig. 66) in position and then filling in around them with refractory material consisting of damp silicious material held together with clay and containing usually some coke breeze, which seems to lessen the chemical activity of the corrosion. The details of lining vary so greatly that no general rules can be given. The number of tuyeres is from 18 to 30, the number of holes in each from 12 to 18, and the size of the holes 3/8 in. (England) or 3/8 to 5/8 in. (America).[1] The correct lining is of the

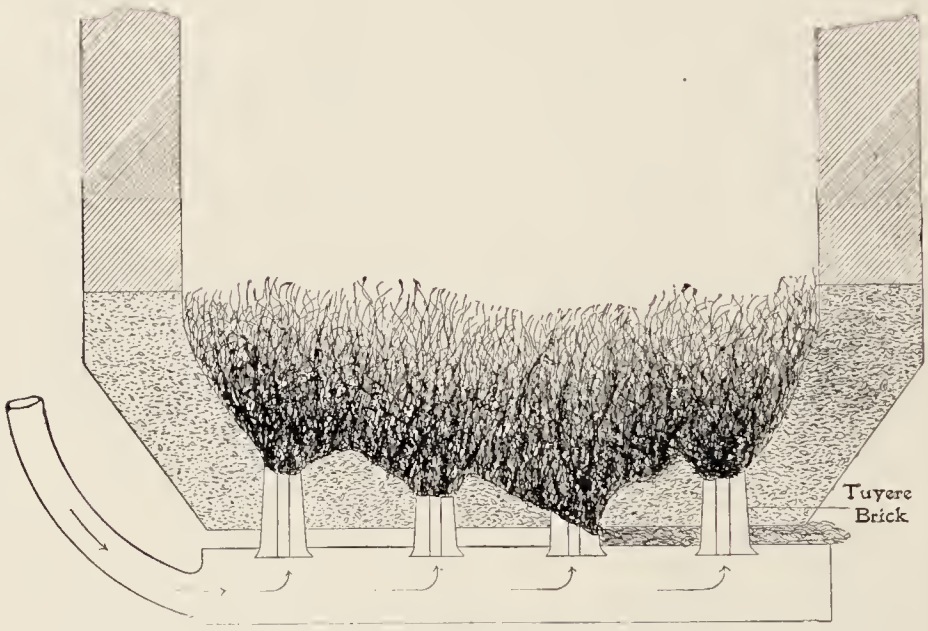


FIG. 66.—CORROSION OF THE BOTTOM LINING OF BESSEMER CONVERTER.

greatest importance and is the most influential factor in determining the life of the bottom, which furthermore depends upon the care in drying, the temperature of blowing, the pressure of blast, and the composition of pig iron. A bottom should dry 36 hours or more. Its life is shortened by (1) hotter blows, (2) longer blows, (3) lower blast pressure (because the blast holds the metal away from the mouths of the tuyeres), and (4) more manganese in the pig iron (because a wet slag is more corrosive). Between heats, when the vessel is on its side receiving the recarburizer,

[1] The acid Bessemer process finds its greatest importance in America, and next to that in England. Germany is the leader in basic Bessemer practice.

pouring into a ladle, or receiving a new charge, the lining of the bottom can be repaired. For instance, if one tuyere eats away faster than its fellows, the excessive corrosion can be prevented by stopping it up with mud, because, if no air passes through the holes, no oxide of iron is formed at their mouths. Or a worn tuyere may be replaced by a new one, etc., etc. These repairs are chiefly made through the wind-box, the back plate of which is removable.

When a bottom is worn out, it is taken away and a new one brought on a car and placed under the converter, which is in the vertical position. Around the top is piled a ring of thick wet mud, and, as the bottom is forced up against the body by hydraulic pressure, the mud is squeezed into a firm joint. Lack of space prevents an account of some of the interesting expedients that are resorted to to stop an occasional leak in this joint without delaying the first heat, which must be avoided if possible, as the first heat on a new bottom is already too liable to be a cold one.

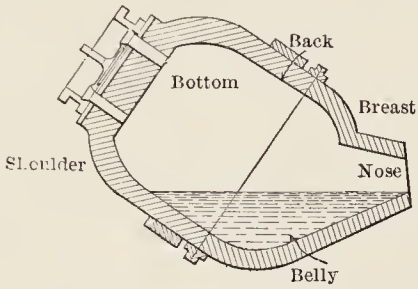


FIG. 67.—CONVERTER PARTS.

Operation of the Converter.—Figures 68 and 69 are sections through a converter plant at different points. In Fig. 68, *A* is the mixer, capable of containing, say, 300 tons of metal; B is the ladle carriage from the blast furnace, from which the ladle *C* has been raised to pour the metal into the mixer. Immediately above *D* is the ladle that is to take the metal from the mixer to the converter, for which it is transferred along a level track until it comes to *E* (Fig. 69), where it is poured into the vessel, now in the horizontal position, as shown by the dotted line. When the metal has been poured in, the wind is turned on and the vessel elevated into the vertical position. The blast now pours through the 18 inches or so of metal in the bottom of the converter in a wide spray of tiny bubbles until the impurities are oxidized, when it is turned again into the horizontal position and the wind cut off. In anticipation of this a predetermined quantity of spiegeleisen has been tapped from the spiegel cupola into the ladle at *H* (Fig. 68). (For soft steel ferromanganese, not spiegeleisen, is used.)

Spiegeleisen is pig iron very high in manganese. Some analyses are given on page 8. It is melted in the spiegel cupola to-

gether with a predetermined amount of high silicon pig iron, and is then used to recarburize the bath in the vessel, for which pur

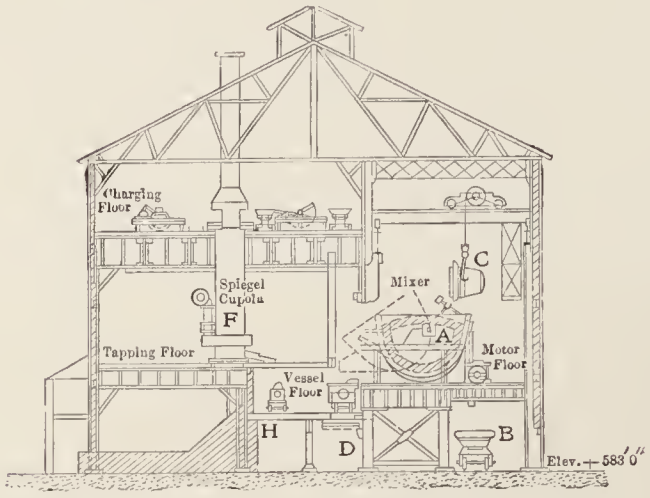


FIG. 68.

pose the ladle is now run into the position *E* (Fig. 69) and its contents poured into the bath.

After the "spiegel reaction" is completed, the steel is poured

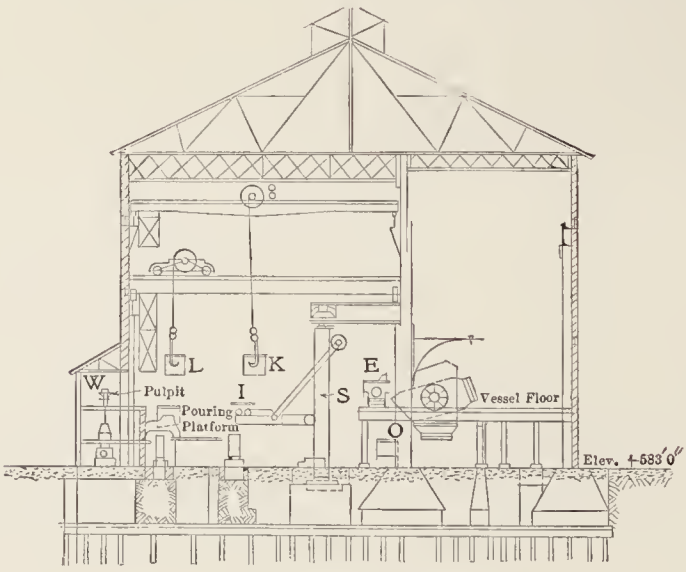
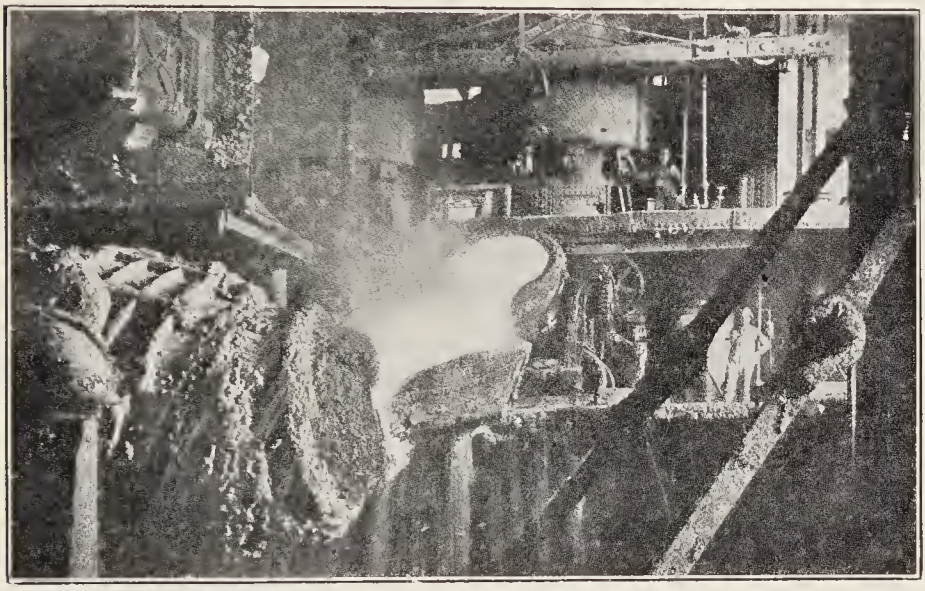


FIG. 69.

from the converter into a ladle held at the point *O* by the jib-crane *I*, or by one of the traveling cranes *K* or *L*. The ladle is then carried over to a position above the ingot molds into which the

steel is to be teemed In pouring the steel into the ladle, the slag is held back in the vessel as much as possible, because this not only furnishes heat for the next operation, but also makes it shorter by as much as 20 or 25 per cent., because the slag, being an oxidized substance, assists in oxidizing the impurities in the next charge.

The turning on and off of the blast and the rotation of the converter is all executed by the blower, who stands upon the pulpit at *W* and operates the various valves, and also judges by eye the



Converter. Cupola.
Ladle.
Runner.

FIG. 70.—POURING METAL INTO THE CONVERTER.

progress of the purification from the appearance of the flame which issues from the mouth of the converter.

Every effort is made by him to so arrange the different operations of the converter, cranes, and ladles and to bring in both spiegeleisen and iron, that each step shall fit into the others without delay to the operation in any of the converters. He also has under his control means for lowering the temperature of the bath, if necessary: (*a*) By ordering an amount of cold steel scrap to be thrown into the mouth of the vessel during the blow[1] and (*b*) by admitting live steam into the converter with the blast. The de-

[1] Scrap is so valuable for use in the open-hearth process that (*b*) is now used much more than (*a*).

composition of the steam very quickly reduces the heat of the blow. Attempts have been made to dispense with the blower, who, on account of the long training and experience necessary, is the most highly paid man in the plant next to the foreman, by judging of the progress of the operation with the spectroscope; but when two or three vessels are blowing at the same time the reflected light from one interferes with the spetroscopic indications of the others. Furthermore, the spectroscope gives no indications of the temperature of the blow, and until the past few years no reliable pyrometer existed suitable for this use.

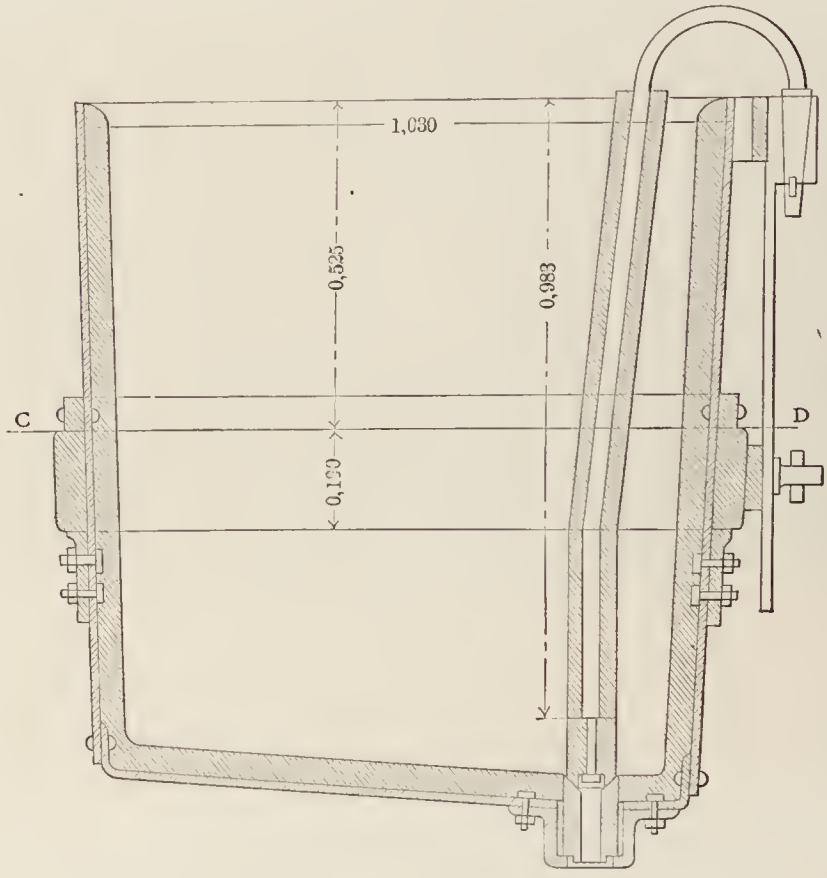


FIG. 71.—FIFTEEN-TON STEEL TEEMING LADLE.

Steel Ladles.—The ladles to receive the steel and teem it into molds are steel shells lined with a cheaper grade of acid refractory material, because the life of these ladles is limited to about six heats by the wearing out of the nozzle, and therefore a more expensive lining would be wasted. The arrangements of nozzles, stoppers, and handles shown in Fig. 71 are provided in order that a

thin stream of steel may be poured into the molds and may be interrupted when a new mold is being brought into place. The slag lies on top of the metal, and when this begins to come out of the nozzle the stopper is let down and the ladle carried over a slag car and turned upside down to dump out the slag. At this time the blower observes the lining of the ladle in order to tell whether the steel was too hot or too cold. If there is a skull of metal frozen inside the ladle, the steel was too cold; if there is no frozen metal, it was too hot; but if there is a spot of metal here and there on the bottom, it was just right.

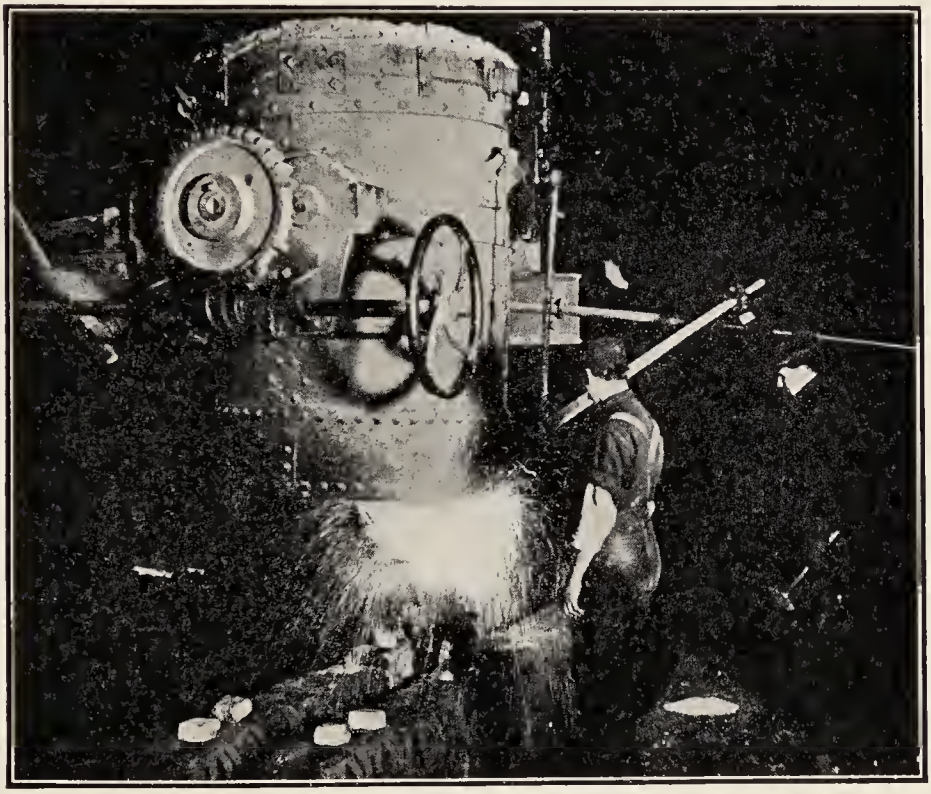


FIG. 72.—TEEMING INTO MOLDS.

Ingot Molds, Stools and Cars.—The arrangement of the molds into which the ingots are to be cast is shown in Fig. 73, which also gives the dimensions of molds commonly used for railroad rails, wire, and pipe. Molds last about 100 heats, after which they are so cracked inside that they are with difficulty lifted off the solidified ingot of steel, and are also very liable to tear it, producing cracks which are not easily welded up later because they become oxidized on the interior. A continuous series of mold cars are

fed into the steel-mill at one end and drawn out, with the ingot inside, at the other end. They should be heated so hot that the palm of the hand will not bear the heat on the outside, and are washed inside with a thin clay wash which prevents the liquid metal sticking to the cast iron. At the pouring platform they are moved forward under the ladle by means of a little finger, which enters a notch in the side of the car and is itself carried on the rod of a hydraulic piston.

FIG. 73.—INGOT MOLDS, STOOL AND CAR.

5000-lb. molds: 7 ft. high, 15 3/4 in. square at top, 19 1/4 in. at bottom; about 2 1/2 in. thickness of cast iron.

Stripping.—As soon as they can be run out to the stripping house, the ingots are solidified sufficiently on the outside for the mold to be removed, leaving the ingot standing on the car ready to be drawn to the rolling-mill. In the majority of cases it is only necessary to place the jaws of the stripping machine under the lugs on the mold, raise it up to a sufficient height, and then transfer it to a stool on a car in the second track of the stripping house.

Sometimes the ingots do not come out so easily, however, and then the plunger is rested on top of the ingot, which is held down by the hydraulic pressure as the mold is drawn upward. Electrically operated stripping machines are now preferred to the older hydraulic type. The empty molds are stored in the yard until they are sufficiently cool to be drawn back to the steel-mill for another charge, and during the wait they are washed inside with clay water, which is quickly dried by the heat of the mold.

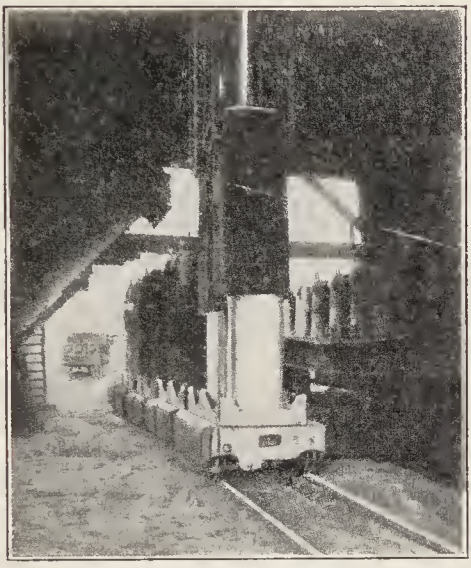


FIG. 74.—STRIPPING.

Chemistry of the Acid Bessemer Process.—If a stream of air be made to impinge upon a melted bath of iron, the metal and impurities will be immediately oxidized, about in proportion to the relative amounts of each present. We may therefore consider the chemistry of the Bessemer process as a union of the oxygen from the tuyeres with the first element it meets, irrespective of relative affinity, and a subsequent attack upon these oxidized elements by unoxidized ones.

Practically no oxygen of the air escapes from the bath uncombined, even though it has but 18 in. of metal to pass through and amounts to more than 5000 cu. ft. per minute,[1] because the blast pressure is made high in order that the air may be broken up into a fine spray of bubbles as soon as it strikes the metal and thus offer a large surface of contact for chemical reaction. As

[1] Air is composed of 20.8 parts, by volume, of oxygen and 79.2 parts of nitrogen, and the amount of blast per minute is 15,000 to 30,000 cu. ft. See analyses of gases in Table XV.

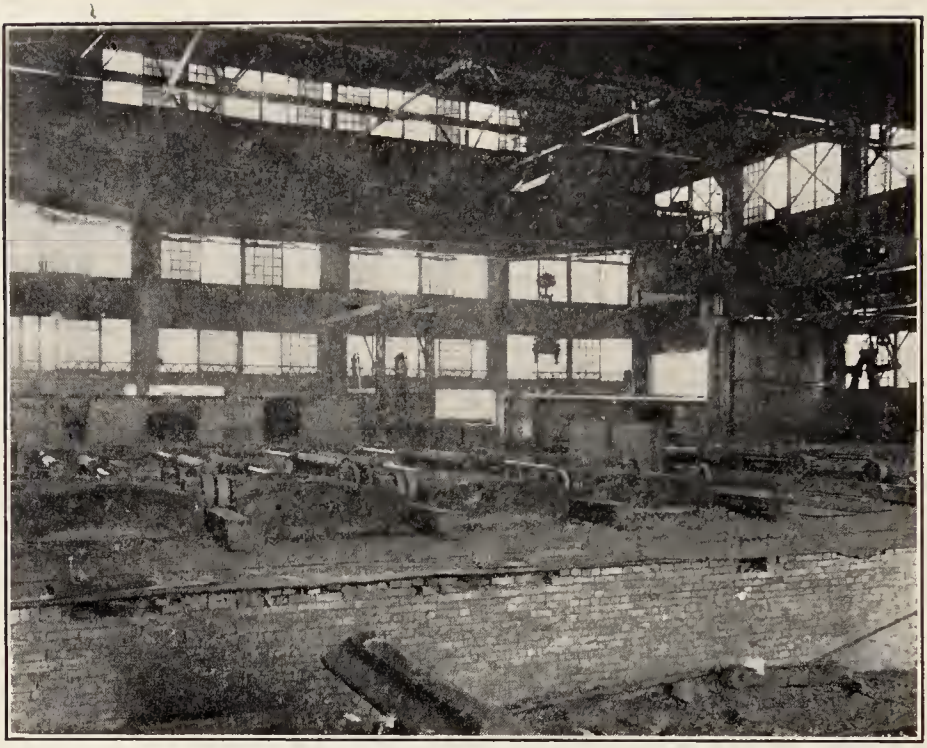


FIG. 75.—SOAKING PIT HEATING FURNACES AT ROLLING MILL WHICH RECEIVE THE RED HOT, NEWLY STRIPPED INGOT.

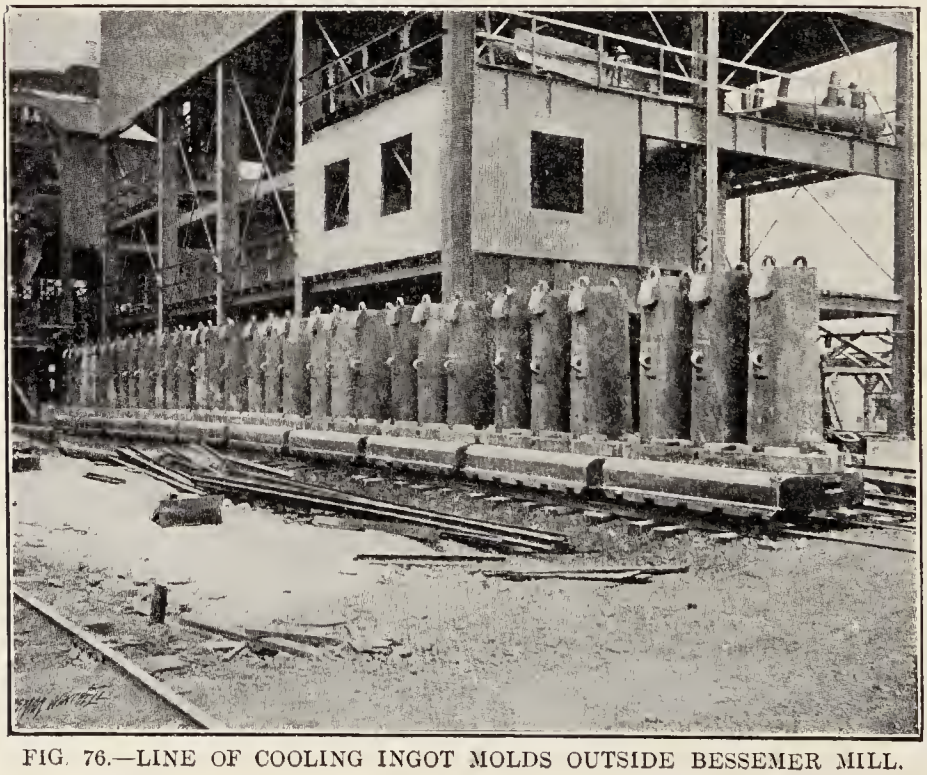


FIG. 76.—LINE OF COOLING INGOT MOLDS OUTSIDE BESSEMER MILL.

iron oxides are easily reduced, and as iron is the predominant element, it especially serves as a carrier of oxygen from the blast to the other elements:

1. $FeO + Mn = Fe + MnO.$
2. $FeO + C = Fe + CO.$
3. $2FeO + Si = 2Fe + SiO_2.$

In the first part of the blow, the oxides of carbon also suffer reduction:

4. $2CO + Si = SiO_2 + 2C.$
5. $CO_2 + Si = SiO_2 + C.$
6. $CO + Mn = MnO + C.$

At a later period this condition is reversed as described on pages 94 to 95.

Equilibrium is therefore established by the elements which have the greatest chemical affinity for oxygen, getting practically all of that agent, either directly or by robbing their neighbors. Some iron oxide survives, however, because it is so predominant in amount that its neighbors cannot quite rob it before a part has united with silica, which is either formed by the oxidation of silicon or else won from the lining:

7. $FeO + SiO_2 = FeSiO_3.$

The ferrous silicate forms a slag with manganese silicate, and this slag will dissolve oxides of iron. Even after the oxide of iron has been so absorbed, it may be reduced by manganese and carbon, although not to the same extent.

Slag Formation.—Manganese oxide unites with silica:

8. $MnO + SiO_2 = MnSiO_3;$

and it is perhaps for this reason that manganese, unless very high (say over 2 per cent.), is removed early in the blow. The silicates of iron and manganese dissolve in each other and form a slag, and this slag will dissolve large amounts of iron oxide, manganese oxide, silica and alumina, the latter coming from the vessel lining. At all times the bath is so violently agitated that the metal and slag are intimately mixed, and the reducing effect of manganese, silicon and carbon on the iron oxide dissolved in the slag limits it in amount. The slag itself therefore serves as a carrier of oxgyen to the impurities.

Critical Temperature.—As the temperature rises, chiefly due to the oxidation of silicon, the chemical affinity of carbon for

oxygen increases relatively more than that of the other impurities, and reaction No. 4 ceases and then reverses:

$$9.\ SiO_2 + 2C = 2CO + Si.$$

What the exact temperature of this reversal in has never been determined, but we may estimate it as being somewhere between

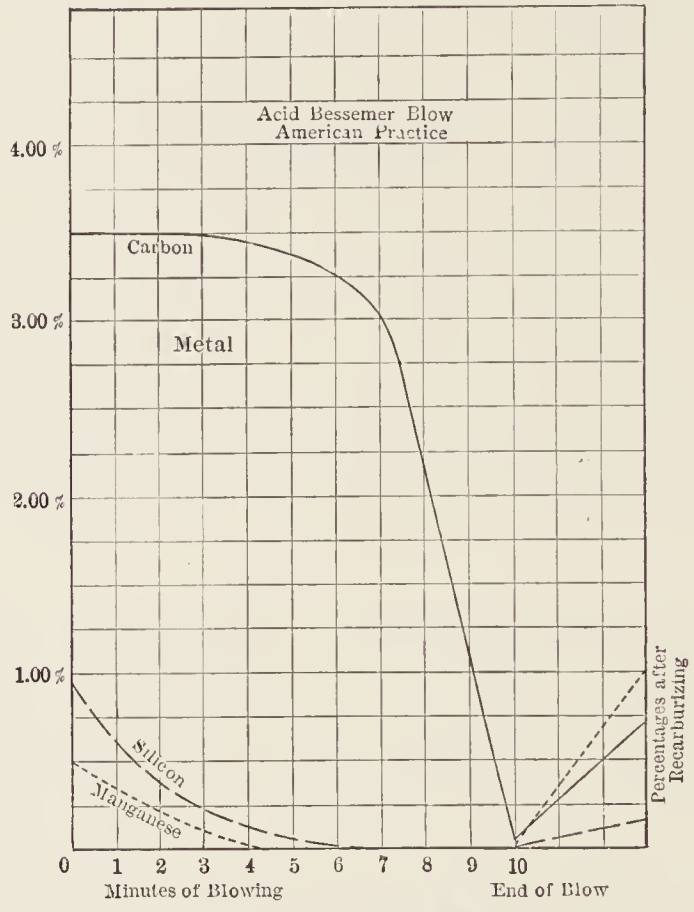


FIG. 77.—ANALYSES OF METAL.

1450° and 1550° C. (2642° to 2822° F.), and unless the silicon is all oxidized before this temperature is reached, we shall have "residual silicon" in the steel. In English Bessemer practice, where silicon is often above 2 per cent. of the pig iron, this is not rare, because the high silicon takes longer to go and also increases the temperature:

$$10.\ Si + 2O = SiO_2 \text{ (generates 180,000 calories).}^1$$

[1] It is immaterial from the heat standpoint whether oxidation takes place directly or as a result of two reactions:

$$2\ Fe + 2O = 2\ FeO \quad \text{(generates 131,400 calories)}$$
$$2\ FeO + Si = SiO_2 + 2\ Fe \quad \text{(generates 48,600 calories)}$$
$$\text{180,000}$$

There is also a critical temperature for manganese oxidation, above which reaction No. 6 is reversed and residual manganese is left in the steel; but this happens only when the manganese in the pig iron is very high. No warning is given that the temperature is approaching these critical points, because no flame—nothing but sparks—comes from the mouth of the converter until carbon

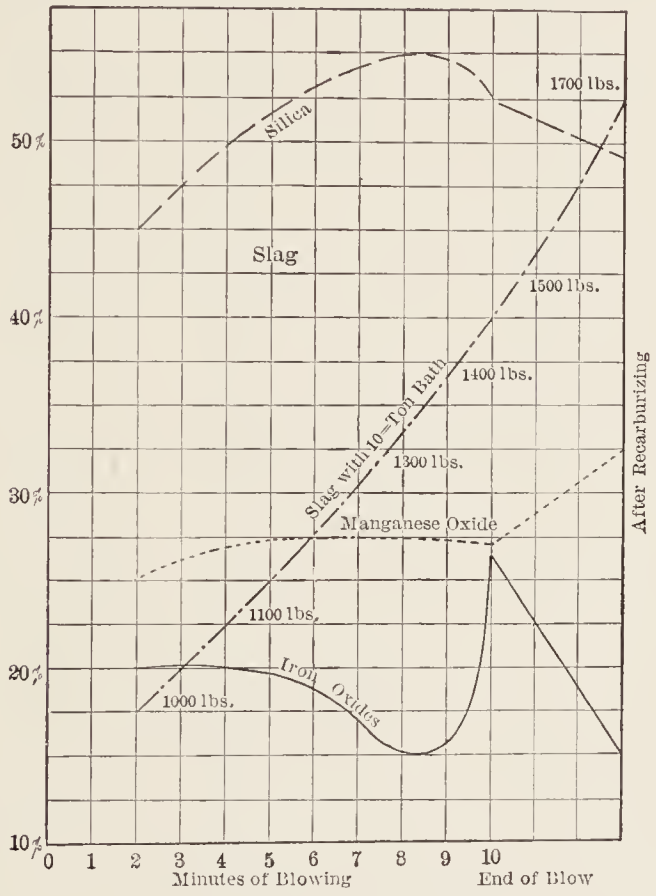


FIG. 78.—ANALYSES OF SLAG.

begins to burn, and therefore no indication is given to the operator of the degree of heat until too late.

Second Period.—The second period begins when the carbon commences to burn, which happens in America only after the silicon and manganese have been almost eliminated, as shown by Tables XIII and XIV and Figs. 77 and 78. During this period the reactions consist principally of the oxidation of carbon, although a little silicon passes off at the same time. Further details will be learned from the tables and figures. It is interest-

ABLE XIII.—REMOVAL OF IMPURITIES IN THE BESSEMER CONVERTER, WIT ACCOMPANYING SLAG-ANALYSES

Time after commencement of blow	Removal of metalloids—per cent.					Authority[1]	Analysis of corresponding slags—per cent.										
	C	Si	Mn	P	S		SiO	Al_2O	FeO	Fe_2O_3	Iron as shots	MnO	CaO	MgO	P	S	
Min. Sec.																	
Pig iron.	2.98	0.94	1.43	0.100	0.06		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	..
2 0	2.94	0.63	0.09	0.104	0.06		42.40	5.63	40.29	4.36	.....	6.54	1.22	0.36	0.008	0.009	..
3 20	2.71	0.33	0.04	0.106	0.06		50.26	5.13	34.24	0.96	.....	7.90	0.91	0.34	0.008	0.009	..
6 3	1.72	0.03	0.03	0.106	0.06		62.54	4.06	21.26	1.93	.....	8.79	0.88	0.34	0.010	0.014	..
8 8	0.53	0.03	0.01	0.107	0.06	Howe. American 39.	63.56	3.01	21.39	2.63	.....	8.88	0.90	0.36	0.014	0.008	
9 10	0.04	0.02	0.01	0.108	0.06		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	..
Steel.																	
9 20	0.45	0.038	1.15	0.109	0.059		62.20	.276	17.44	2.90	.....	13.72	0.87	0.29	0.010	0.011	..
								Al_2O_3 & P_2O_5									
Pig iron.	3.55	2.39	0.49	0.09	.....		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	..
8 0	3.21	1.08	0.15	.....	.....		62.65	7.98	1.93	....	10.52	15.78	0.65	0.52	.....	.....	..
15 0	1.25	0.11	0.13	0.09	.....		73.24	4.51	0.00	....	8.72	11.83	1.11	0.64	.....	.....	..
17 0	0.207	0.06	0.13	0.08	.....	King. American 40.	75.63	5.19	0.00	....	7.70	10.92	0.96	0.38	.....	.....	..
18 0	0.034	0.04	0.10	.....	.....		61.30	4.24	13.47	....	9.12	10.82	0.75	0.29	.....	.....	..
Steel.	0.370	0.06	1.17	0.09	.....		64.15	5.71	13.95	....	2.39	12.81	0.75	0.24	.....	.....	..
								Al_2O_3									
Pig iron.	3.93	1.96	3.46	0.040	0.018		40.95	8.70	0.60	....	.....	2.18	30.35	16.31	0.01	0.34	C
After slagging	2.465	0.443	1.645	0.040	trace	Bell.	46.78	4.65	6.78	....	.....	37.00	2.98	1.53	0.03	0.04	t
End of boil.	0.949	0.112	0.429	0.045	trace	English 41.	51.75	2.98	5.50	....	.....	37.90	1.76	0.45	0.02	trace	t
End of blow.	0.087	0.028	0.113	0.045	trace		46.75	2.80	16.86	....	.....	32.23	1.19	0.52	0.01	trace	t
Pig iron.	4.00	1.02	1.83	.....	.....		50.20	3.86	1.80	.....	.....	5.44	27.22	10.88	.....	.....	..
3 0	4.30	0.03	0.22	.....	.....		55.26	2.86	14.20	.....	.....	26.31	0.62	0.22	.....	.....	..
4 45	0.90	0.03	0.12	.....	.....		47.20	2.70	18.52	.....	.....	31.01	0.38	0.14	.....	.....	..
5 45	0.10	0.03	0.09	.....	.....	°Bangbro. Sw. 42.	40.50	2.24	31.19	.....	.....	25.43	0.32	0.11	.....	.....	..
Pig iron.	3.94	1.14	0.64	.....	.....		46.50	12.90	0.90	.....	.....	0.58	32.07	6.75	.....	.....	..
2 15	4.20	0.04	0.12	.....	.....		48.76	0.78	34.72	.....	.....	13.95	2.60	0.24	.....	.....	..
4 30	1.10	0.03	0.12	.....	.....		59.82	0.98	21.08	.....	.....	15.48	3.25	0.30	.....	.....	..
5 0	0.05	0.01	0.06	.....	.....	°Langhytt'n. Sw. 42.	48.48	0.72	35.82	.....	.....	12.29	2.35	0.21	.....	.....	..
Pig iron.	4.49	1.08	0.83	.....	.....		51.00	2.56	0.90	.....	.....	3.40	31.80	9.03	.....	.....	..
3 0	3.87	0.03	0.11	.....	.....		53.44	1.84	20.24	.....	.....	23.90	0.44	trace	.....	.....	..
5 0	1.30	0.03	0.09	.....	.....		57.80	1.94	17.04	.....	.....	22.80	0.46	.....	.....	.....	..
5 45	0.33	0.02	0.07	.....	.....	Sandviken. Sw. 42.	55.76	1.58	18.48	.....	.....	22.23	0.36	.....	.....	.....	..
Pig iron.	4.35	0.88	1.15	.....	.....		47.16	5.83	0.77	.....	.....	2.14	21.79	22.18	.....	.....	..
2 30	4.10	0.10	0.15	.....	.....		53.26	2.28	13.50	.....	.....	29.76	0.42	0.23	.....	.....	..
5 30	1.00	0.05	0.15	.....	.....		62.34	3.90	9.54	.....	.....	23.70	0.60	0.28	.....	.....	..
6 30	0.08	0.04	0.08	.....	.....	Nykroppa. Sw. 42.	44.52	2.14	30.60	.....	.....	21.39	0.38	0.21	.....	.....	..
Pig iron.	4.22	1.06	5.12	.....	.....		46.72	4.36	0.70	.....	.....	11.16	19.10	18.37	.....	.....	..
4 15	4.20	0.43	3.26	.....	.....		45.87	3.08	4.20	.....	.....	46.38	1.26	0.54	.....	.....	..
8 35	1.30	0.12	0.85	.....	.....		39.07	2.49	6.24	.....	.....	52.26	0.70	0.29	.....	.....	..
9 20	0.55	0.07	0.43	.....	.....	Westanfors. Sw. 42.	37.63	2.94	9.45	.....	.....	48.92	1.00	0.46	.....	.....	..
															P_2O_5		
Pig iron.	3.5	1.70	.....	1.50	0.05		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	..
3 0	3.6	0.80	.....	1.50	0.05		32.6	.....	7.26	.....	.....	.....	.....	.....	0.60	.....	..
6 0	3.4	0.28	.....	1.63	0.05		42.6	.....	2.57	.....	.....	.....	.....	.....	0.15	.....	..
9 0	2.4	0.05	.....	1.43	0.05		36.0	.....	5.91	.....	.....	.....	.....	.....	1.60	.....	..
12 0	0.09	0.01	.....	1.42	0.05	Basic. Bell. 41a.	35.6	.....	6.17	.....	.....	.....	.....	.....	2.61	.....	..
14 30	0.075	0.0	.....	1.20	0.05		33.0	.....	7.89	.....	.....	.....	.....	.....	5.66	.....	..
16 30	0.0	0.0	.....	0.08	0.05		15.6	.....	13.43	.....	.....	.....	.....	.....	15.06	.....	..

[1] See No. 52.

TABLE XIV.—REMOVAL OF IMPURITIES IN THE BESSEMER PROCESS

Time after commencement of blow	Removal of metalloids—per cent.					References and remarks
	C	Si	Mn	P	S	
Min. Sec.						
Pig iron.	3.52	3.00	1.25	.....	.....	German method. "Leaving Silicon in the Bath," *Stahl und Eisen,* vol. iii, pp. 262–264.
5 0	3.6	2.0	0.60	.....	.....	
10 0	3.3	1.25	0.20	.....	.....	
15 0	2.5	0.75	0.10	.....	.....	
20 0	1.0	0.65	trace	.....	.....	
25 0	trace	0.35	.....	.....	.....	
Pig iron.	3.5	3.0	0.75	.....	.....	German method. Same reference.
5 0	3.6	1.75	0.25	.....	.....	
10 0	3.3	1.25	trace	.....	.....	
15 0	2.5	0.9	.....	.....	.....	
20 0	1.0	0.7	.....	.....	.....	
25 0	trace	0.5	.....	.....	.....	
Pig iron.	3.52	1.85	1.93	.....	.....	German method. Carl Rott. 31
4 30	2.78	1.21	1.69	.....	.....	
13 0	0.43	0.93	1.00	.....	.....	
16 0	0.05	0.28	0.37	.....	.....	
Steel.....	0.23	0.27	0.62	.....	.....	
Pig iron.	3.57	2.26	0.04	.....	.....	English method. Carl Rott. 31
6 0	3.95	0.95	trace	.....	.....	
12 0	1.64	0.47	trace	.....	.....	
18 0	0.19	trace	trace	.....	.....	
Steel.....	0.37	trace	0.54	.....	.....	
Pig iron.	3.270	1.952	0.086	0.048	0.014	English method. Snelus. See *Encyclopædia Britannica,* American ed., vol. xiii, p. 334.
6 0	2.170	0.795	trace	0.051	trace	
9 0	1.550	0.635	trace	0.064	trace	
13 0	0.097	0.020	trace	0.067	trace	
Steel.....	0.519	0.033	0.309	0.053	trace	
Pig iron.	3.5	2.25	1.0	.....	.....	*Stahl und Eisen,* vol. iii, pp. 262–264.
5 0	3.6	1.0	0.35	.....	.....	
10 0	3.3	0.5	0.2	.....	.....	
15 0	3.25	0.2	trace	.....	.....	
20 0	2.0	0.1	.....	.....	.....	
25 0	trace	trace	.....	.....	.....	

TABLE XIV.—REMOVAL OF IMPURITIES IN THE BESSEMER PROCESS.—*Continued.*

Time after commencement of blow	Removal of metalloids—per cent.					References and remarks
	C	Si	Mn	P	S	
Pig iron.	3.50	1.50	0.71	1.57	0.16	"Basic Process," *Stahl und Eisen,* vol. iii, pp. 262–264.
5 0	3.55	0.50	0.56	1.60	0.14	
10 0	2.35	0.09	0.27	1.43	0.13	
15 0	0.07	trace	0.12	1.22	0.12	
18 0	trace	.....	trace	0.08	0.10	
Pig iron.	2.97	0.53	0.61	1.22	0.15	"Basic Process," by Müller, at Hörde, *Encyc. Brit.*, p. 346.
4 30	2.480	0.009	0.247	1.250	0.206	
9 15	0.811	0.0	0.0	1.320	0.262	
11 15	0.049	0.0	0.0	0.786	0.262	
13 0	0.0	0.0	0.123	0.021	0.206	

ing to note that the phosphorus and sulphur in the metal are not eliminated, because the acid slag will not dissolve them even if they become oxidized. For this reason the percentage of these impurities increases slightly during the blow, because their actual weight remains the same, while the weight of the bath decreases.

Gases.—In connection with Table XV it is interesting to note what a large proportion of the carbon is oxidized to the monoxide, and this is the more important because this formation generates only 29,160 calories, while the higher oxidation generates more than three times as much:

$$C + 2O = CO_2 \text{ (generates 97,200 calories).}$$

Thus a large amount of heat is wasted, and is generated only when the flame passes out of the mouth of the converter and unites with more oxygen. When the heat of a charge is too low, it is customary at some plants to tip the converter forward or backward, so that a few tuyere holes will be above the level of the bath and will blow free air into the interior of the converter. This results in a portion of the carbon monoxide being oxidized to carbon dioxide inside the converter, and is a limited means of making the blow hotter. Oxidation of additional iron also increases the heat generated.

TABLE XV.—ANALYSES OF BOTTOM-BLOWN CONVERTER-GASES

Time after starting blow	Per cent.					Reference[1]
	CO	CO_2	O	H	N	
2 min.	.....	10.71	0.92	.....	88.37	Sir Lothian Bell. 37
4 min.	3.95	8.59	.....	0.88	86.58	
6 min.	4.52	8.20	.....	2.00	85.28	
10 min.	19.59	3.58	.....	2.00	74.83	
12 min.	29.30	2.30	.....	2.16	66.24	
14 min.	31.11	1.34	.....	2.00	65.55	
18 min.	End of blow.					
3 to 5 min.	.....	9.127	4.762	.....	86.111	38
9 to 10 min.	17.555	5.998	1.699	0.908	73.840	
21 to 23 min.	19.322	4.856	0.967	1.120	73.735	
26 to 27 min.	14.311	1.853	0.550	1.699	81.587	
2 to 3 min.	.....	6.608	7.256	.....	86.137	38
8 to 10 min.	15.579	5.613	1.296	1.112	76.400	
12 to 15 min.	25.580	4.144	0.980	1.040	68.256	
17 to 19 min.	25.606	2.995	1.318	1.120	68.961	

[1] See No. 52.

Slag.—In Table XIII the lime and magnesia in the slag come from a small amount of blast-furnace slag which finds its way to the converter through the mixer, in spite of efforts made to hold it back at all points when pouring. Because the blast-furnace slag is basic, it has the effect in the converter of making the slags wet and sloppy, and therefore increasing the loss. Although the iron as shot is only shown in one case, this is not because it is absent in the other cases, but merely because it was not determined. At all times the slag carries a great many pellets of iron, which should be added to the combined iron, since they represent a loss in the process. It is interesting to note how closely the amount of iron in the slag, after the spiegel addition, approximates 15 per cent.,[1] and there seems to be a chemical balance which fixes this amount as a condition of equilibrium. When the silicon in the pig iron is higher, and therefore the amount of slag made is larger, there is a slightly lower percentage of iron oxide

[1] Not including pellets, which average 6 to 8 per cent. more.

in it. The practice of "side blowing for heat," described above, has the effect of increasing the amount of iron oxide in the slag by increasing the oxidizing influences in the interior of the converter. The rise in manganous oxide in the slag during recarburizing is, of course, due to the formation of MnO by the action of the manganese on the oxygen of the bath, while the iron oxide in the slag is reduced at the same time by the action of manganese and carbon.

The weight of slag at different periods of the Bessemer process has been calculated by H. H. Campbell[1] from its analyses, with the following average results:

TABLE OF SLAG WEIGHTS IN BESSEMER PROCESS

Percentage of blow finished		Pounds of slag	Percentage of charge
20	Silicon flame	1035	4.5
36	Brightening	1146	5.1
66	Carbon flame	1255	5.5
89	Full carbon flame	1385	6.1

The final amount of slag made will probably average about 7 1/2 to 8 per cent. of the weight of the metal produced, or, roughly, 7 per cent. of the weight of the pig iron charged.

Flame.—A flame is the result of burning gas, and as practically the only gas in this process is carbon monoxide, there is no flame except during the period when the carbon is burning. In the first part of the blow a large number of small sparks issue from the mouth of the converter, consisting mainly of pellets of iron and slag ejected by the blast. At the end of the first two o three minutes, a small tongue of reddish-yellow flame begins to pour from the mouth, showing that the carbon is beginning to be oxidized. This soon increases in size and brilliancy until a white-hot flame, 30 ft. in height, pours from the vessel with a loud roaring sound caused by the boiling of the bath and the passage of the blast and gas through it. This boil lasts until the end of the operation, and the bath is at all times violently agitated and intimately mixed with the slag, which greatly facilitates the reaction between the two. The process at this period

[1] See page 158 of No. 2. Old edition, 1904.

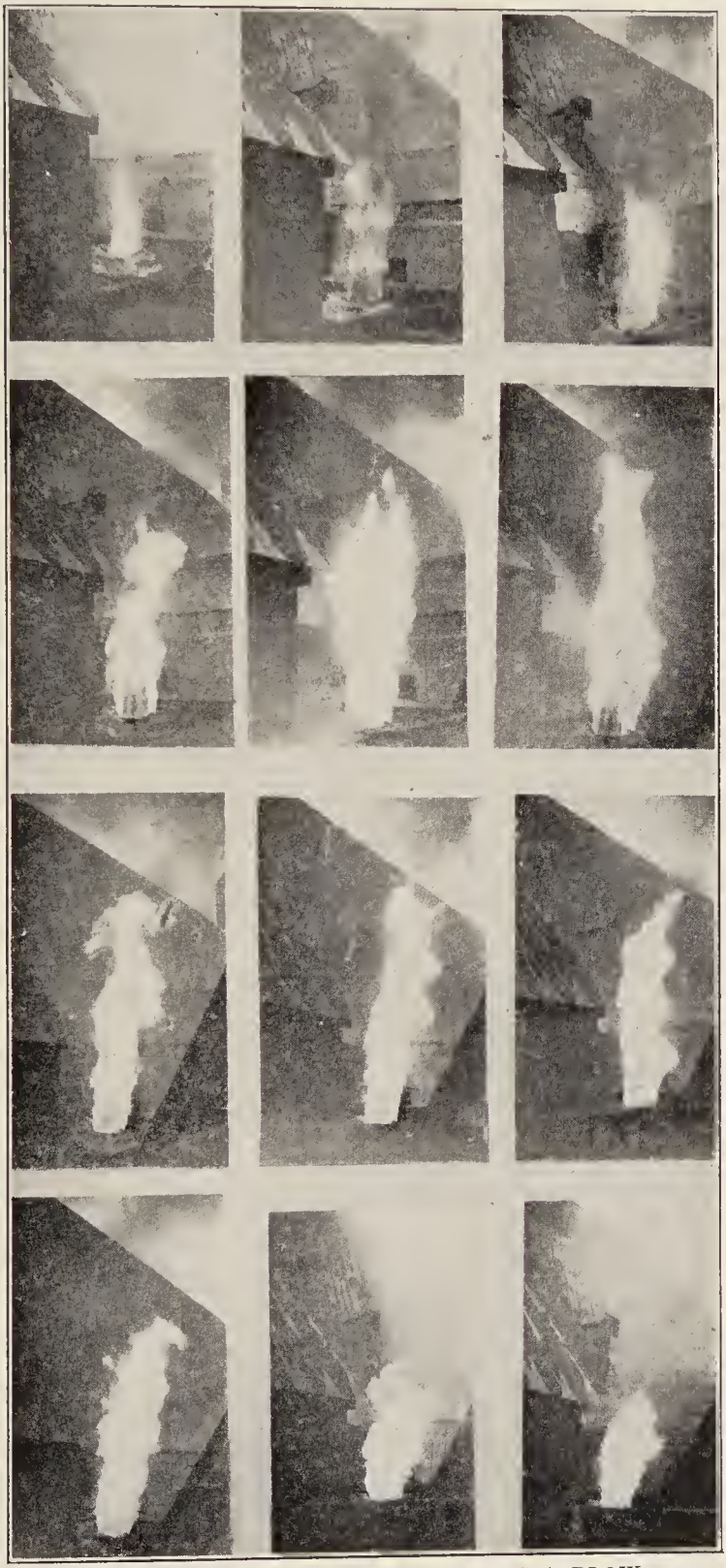


FIG. 79.—BESSEMER FLAMES DURING A BLOW.

presents a spectacle which is almost unmatched as a pyrotechnic display. Soon the flame begins to flicker or "feather" at the edges, as a warning that the carbon is becoming low, and finally it shortens or drops, whereupon the converter is immediately turned down and the blast stopped. The carbon at this time will be about 0.03 to 0.10 per cent., depending on how "young" or how "full" was the blowing.

At all times there is a varying amount of slag and metal thrown out of the mouth, so that the converter may be likened to a fountain of sparks, the great bulk of which consists of slag. Throughout the blow there is also a constant stream of fume issuing with the flame. It is a brownish-red smoke, which rises to a good height and consists principally of oxide of iron and manganese. Dr. Charles F. Chandler, Professor of Chemistry at Columbia University, while observing this smoke at the Homestead steel-works, suggested to me that it might be due to the formation in the bath of iron carbonyl, a volatile compound of iron, carbon and oxygen ($Fe(CO)_5$), and perhaps of manganese carbonyl also.

Loss.—The difference in weight between the pig iron charged into the converter and the steel ingots made will be 8 per cent. in good practice, although running above that (say to 10 per cent.) in some mills. This is distributed approximately as follows:

Carbon burned	3.5 per cent.
Silicon burned	1.0 per cent.
Manganese burned	0.5 per cent.
7 per cent. slag @ 15 per cent. Fe	1.0 per cent.
7 per cent. slag @ 7 per cent. iron pellets	0.5 per cent.
Volatilized and ejected	1.5 per cent.
	8.0 per cent.

Recarburizing.—It might be thought that a more economical method could be found than that of burning up all of the carbon in the pig iron and then adding the desired amount, and in fact such a method was employed in Sweden, where the carbon was burned down to the desired point, as estimated by the appearance of the sparks issuing from the converter, the vessel being then turned down and the charge held until a hammer-test confirms this estimate. Such a complicated procedure, however, requires a hotter bath and very slow working, and it is much cheaper to burn the carbon until the drop of the flame and then add the requisite amount. In making rail-steel to contain about 0.50 per cent. carbon, we will add to 15 tons of blown metal about

3000 lb. of melted spiegeleisen, containing roughly 6 per cent. of carbon, 12 per cent. of manganese, and 1.50 per cent. of silicon. The mixture charged into the spiegel cupola for melting must be higher in manganese than this, as there is a loss into the cupola slag by oxidation.

In making dead-soft steel for wire, material to be welded, etc., we add ferromanganese as high in manganese as possible. This material will contain about 7 per cent. of carbon, 80 per cent. of manganese, and 13 per cent. of iron. It is only necessary to add about 500 lb. to a 15-ton bath, and therefore it will dissolve without being melted, although it is customary to heat it to a red heat in order to lessen the chilling of the metal. This dead-soft material will then have the requisite amount of manganese, but will be low in carbon and frequently less than 0.01 per cent. in silicon. It is not improbable that pure manganese metal, if it were readily obtainable, would be used in many cases instead of ferromanganese, in order that the carbon might be still lower. Ferromanganese and spiegeleisen are made in the blast furnaces by smelting very high manganese ores in a manner somewhat similar to the smelting of pig iron.

The chemistry of the recarburizing operation is important. The recarburizer is added both to give certain elements to the steel and to take certain impurities out of it. The importance of this second function will be appreciated on recalling that the makers of Bessemer steel were not able to produce a marketable product until they learned to take oxygen out of the liquid bath by means of manganese added with the recarburizer. Finally, the chemistry of the recarburizing operation is complicated by the circumstance that some reactions occur between the recarburizer and the slag of the process.

Deoxidizing the Bath.—The carbon, manganese and silicon contained in the recarburizer will all deoxidize iron according to the following type reactions:

(a) $Mn + FeO = MnO + Fe$.
(b) $3C + Fe_2O_3 = 3CO + Fe$.
(c) $Si + 3FeO = FeO_2.SiO_3 + 2\ Fe$.

Of these, manganese is the most powerful deoxidizer and will come nearest to ridding the bath of oxide. The CO has the disadvantage of being somewhat soluble in the molten metal; consequently, although large volumes of CO gas escape from the steel during the "spiegel reaction," there is, under normal condi-

tions, a constant evolution up to the time when the metal becomes solid, and there is probably even a small amount of CO retained by the solid metal. This escaping gas is a cause of blow holes, as described in Chapter VII. Silicon not only reduces iron oxide, but also is a prime factor in preventing these blow holes, as will also be described in Chapter VII. The oxides of manganese and silicon tend to separate themselves from the liquid bath and it is thus that they remove the oxygen; whereas, the oxides of iron are much more readily retained by the steel. Nevertheless, the removal of oxygen by manganese and silicon is not complete; because firstly, the deoxidation of the FeO and Fe_2O_3 is not complete and secondly, the oxides of manganese and silicon do not completely separate from the steel, but, on account of lack of fluidity, remain in tiny particles entangled in the solidified mass. Rail steels will probably contain 0.20 to 0.30 per cent. of entangled oxides.[1] Unless there be an excess of manganese and silicon necessary to fulfill reactions (a) and (c), their deoxidized effect is far from complete, and it is partly on this account that the recarburizer is so calculated as to leave about 0.70 to 1.10 per cent. of manganese and 0.10 to 0.20 per cent. of silicon in rail steel.

Reactions Between Recarburizer and Slag.—The slag being an oxidized product and the recarburizer being essentially a reducing agent, there is always a certain interchange of elements between the two, the slag giving up some of its oxygen to the carbon and manganese of the recarburizer, and the latter contributing manganese to the slag, both by virtue of reaction (a) and of the following:

$$\text{(d)}\quad FeO(SiO_2)_2 + Mn = MnO(SiO_2)_2 + Fe.$$

It will be observed by the analysis in Table XIII and especially by Fig. 78, that the slag is decreased in iron oxides and increased in manganese oxide as a consequence of the recarburizing operation. It will also be observed in the same places that there is more iron oxide reduced than manganese oxide contributed and this effect is produced by direct reduction of iron, by means of CO, in accordance with the following reaction:

$$\text{(e)}\quad 2FeO.SiO_2 + CO = FeO(SiO_2)_2 + CO_2 + Fe.$$

Calorific Equation of the Acid Bessemer Operation.—The pre-

[1] In this connection it is interesting to note the effect of titanium in supplementing the deoxidizing effect of manganese and silicon and the consequent superiority of titanium treated rails, which will be discussed on page 169.

dominant part that silicon plays in furnishing heat for the acid Bessemer process is shown by a calorific calculation. In making this, let us assume that we have a charge of pig iron weighing 30,000 lb., and that we burn: silicon = 1.00 per cent.; manganese = 0.40 per cent.; carbon = 3.50 per cent.; iron = 2.00 per cent. And let us assume further that the average temperature during the operation will be 1500° C., and that the atmosphere is at 0° C. Then:

	Pound-calories	Surplus pound-calories
$Si + 2O = SiO_2$ produces	1,900,000	
28.4 2×16		
300 lb.[1] + 338 lb. = 638 lb.		
338 lb. of oxygen = 1470 lb. air.		
Specific heat air = 0.268 cals. per lb.		
1470 lb. × 1500° C. × 0.268 =	591,000	
		1,309,000
Mn + O = MnO produces	198,000	
55 16		
120 lb.[2] + 35 lb. = 155 lb.		
35 lb. oxygen = 152 lb. air.		
152 lb. × 1500° C. × 0.268 =	61,000	
		137,000
C + O. = CO produces	2,552,000	
12 16		
1050 lb. + 1400 lb. = 2450 lb.		
1400 lb. oxygen = 6087 lb. air.		
6087 lb. × 1500° C. × 0.268 =	2,447,000	
		105,000
Fe + O = FeO produces	704,000	
56 16		
600 lb. + 171 lb. = 771 lb.		
171 lb. oxygen = 743 lb. air.		
743 lb. × 1500° C. × 0.268 =	299,000	
		405,000
Total net heat from chemical reactions =		1,956,000

[1] 30,000 lb. × 1 per cent. = 300 lb.

[2] 30,000 lb. × 0.40 per cent. = 120 lb.

Now let us suppose that the specific heat of the metal is 0.20 calories per pound, per degree Centigrade; then how many degrees will it be raised by the heat produced in the chemical reactions of the blow?

30,000 lb. × 0.20 cals. = 6,000 cals. per 1° C.

1,956,000 cals. ÷ 6,000 cals. = 326° C. Answer.

This simple calculation neglects the heat lost by radiation through the vessel lining, and the heat necessary to raise the silicon, manganese and carbon of the bath from their temperature at the beginning of the blow, to 1500° C., and also leaves out of account the heat produced by the combination of FeO and MnO with SiO_2 to form the slag. All these figures are relatively less important, but those who desire to calculate with greater delicacy should consult J. W. Richards' very thorough little book, No. 6, Part II.

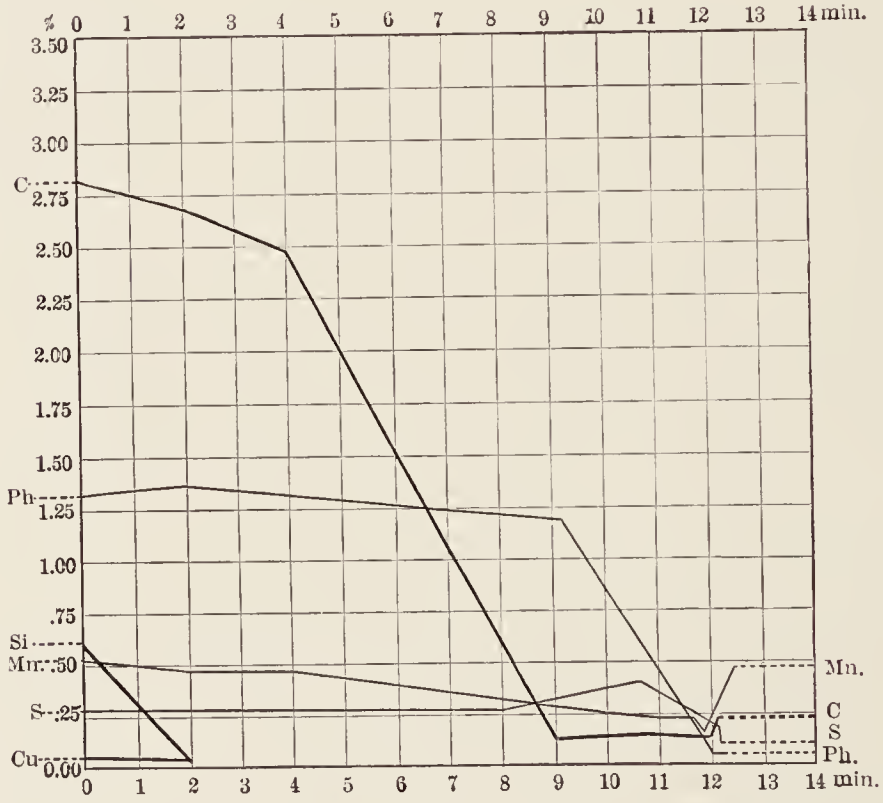


FIG. 80.—REMOVAL OF IMPURITIES IN BASIC BESSEMER PROCESS.

Basic Bessemer Process.—The basic vessel is mechanically the same as the concentric acid vessel, but the lining is made of calcined dolomite held together by about 10 per cent. of tar and rammed in around a pattern while still warm. In ramming up the bottom wooden pins are rammed in with the lining, and when withdrawn they leave 1/2-in. tuyere-holes, through which the blast enters. The object of the basic lining is to resist the chemical action of the basic slag, and it is not desired to have it enter in any way into the chemical reaction. Therefore, before

beginning the blowing, lime is added to the bath, equivalent in weight to 14 to 20 per cent. of the iron, in order that it may form a basic slag, take up all the silica formed by oxidation, and prevent this silica from corroding the lining. The greater the amount of acid-making elements in the pig iron—i.e., silica and phosphorus—the more lime must be added to flux them.

Chemistry of the Basic Process.—There is a degree of similarity between the removal of impurities in the acid blow and in the first part of the basic blow, as will be observed in the analysis in Table XIII, and in Fig. 80. Silicon is removed more rapidly in the basic process, however, both because it is less in amount and because its oxide is greedily absorbed by the basic slag. Manganese, on the contrary, goes more slowly, because its amount is larger and it is not attracted by the slag. Indeed it is not uncommon to find "residual manganese" after a basic blow, and this is considered an advantage because it reduces the amount of manganese necessary to deoxidize the bath. Carbon passes off after the silicon, and the phosphorus does not begin to be substantially removed until after the carbon is practically eliminated.[1] Consequently the drop of the flame really marks the beginning of phosphorus removal.

After-blow.—This final, dephosphorization, period of the basic blow is known as the "after-blow," because it follows what corresponds roughly to the ordinary blow of the acid process. During this after-blow phosphorus is rapidly eliminated and absorbed by the slag. We have no means of knowing by the appearance of the flame how this chemical reaction proceeds, and therefore the after-blow is continued on the basis of experience, by blowing for a certain number of minutes, or else a certain number of revolutions of the blowing engine. Phosphorus goes into the slag in the form of a lean phosphate of lime perhaps having the formula $(CaO)_4P_2O_5$, which corresponds to about 60 per cent. of lime and 17 per cent. of phosphorus. A variable amount of sulphur is also eliminated during the after-blow and goes into the slag in the form of CaS. Some also may be volatilized as oxides of sulphur. A fluid slag and the presence of manganese both assist in the removal of sulphur, which is sometimes as much as 75 per cent. of that present. The addition

[1] In short, we have here a reversal of the action in the Bell-Krupp Process, and for a reason already explained, namely, that carbon has a higher affinity for oxygen at high temperatures, such as prevail in the Bessemer process, but has a lower affinity for oxygen at low temperatures, such as prevail in the Bell-Krupp Process.

of a certain amount of oxide of iron as a flux with the lime aids in producing a fluid slag and also gives a slightly higher yield of steel.

Recarburization.—The bath must not be recarburized in the presence of a basic slag because the latter gives up phosphorus by reduction and the metal is "rephosphorized." What the chemical action is that produces this "rephosphorization" is not clearly known, but it is probable that manganese is an important factor; hence an additional reason for adding as little manganese after the blow as possible, although this cannot be well controlled as the metal is more oxidised in the basic than in the acid blow, and therefore requires a larger addition of manganese to render it free from "red-shortness" and "rottenness." The difficulty is avoided in great part by pouring off all the basic slag possible, and then holding more back in the vessel when the metal is poured into a ladle. The recarburization then takes place in the ladle instead of in the vessel. The other chemical reactions of the recarburizing operation are similar to those given under the acid process. (See also page 136.)

Slag.—The proportion of basic slag made will naturally be greater than that of acid slag, and will usually total about 25 per cent. of the weight of the metal. It is important to so control the blow that a slag shall be produced containing 15 per cent. or so of phosphoric acid, as this makes it salable as an agricultural fertilizer. The amount of iron in the slag should not be above 10 per cent. in oxidized form, although this will be increased by a few per cent. of pellets.

Loss.—The loss of metal will be much higher than in the acid process, averaging perhaps 13 to 17 per cent., a part of which is due to the fact that the pig iron used contains a larger amount of impurities to be oxidized:

Carbon	3.7 per cent.
Silicon	0.5 per cent.
Manganese	1.5 per cent.
Phosphorus	2.5 per cent.
25 per cent. of slag @ 9 per cent. Fe	2.3 per cent.
Pellets	1.0 per cent.
Fume and ejected	1.5 per cent.
	13.0 per cent.

Calorific Equation.—Phosphorus is the main source of heat in the basic Bessemer process as shown by the following calculation:

TABLE XVI.—CALORIFIC EQUATION OF THE BASIC BESSEMER PROCESS

Charge: 30,000 lb.

Analysis: 0.50 per cent. silicon burned;
1.60 per cent. manganese burned;
3.50 per cent. carbon burned;
2.50 per cent. phosphorus burned;
3.00 per cent. iron burned;

Temperature of atmosphere = 0° C.;
Specific heat of air = 0.268 pound-calories per 1° C.;
Specific heat of metal = 0.20 pound-calories per 1° C.;
Average temperature of blow = 1500° C.

Principle of calculation same as in Acid Bessemer Operation, p. 105.

Reactions.	Pound-calories.	Surplus pound-calories.
2 P + 5 O = P_2O_5 produces.....	4,420,000	
62 80		
750 lb. 968 lb.		
4209 lb. air × 1500° C. × 0.268 = ...	1,692,000	
		2,728,000
Si + 2 O = SiO_2 produces.....	950,000	
28.4 32		
150 lb. 169 lb.		
735 lb. air × 1500° C. × 0.268 = ...	295,000	
		655,000
Mn + O = MnO produces.....	794,000	
55 16		
480 lb. 140 lb.		
608 lb. air × 1500° C. × 0.268 = ...	244,000	
		550,000
C. + O = CO produces.....	2,552,000	
12 16		
1050 lb. 1400 lb.		
6078 lb. air × 1500° C. × 0.268 = ...	2,447,000	
		105,000
Fe + O = FeO produces.....	1,056,000	
56 16		
900 lb. 257 lb.		
1118 lb. air × 1500° C. × 0.268 = ...	449,000	607,000
Total net heat from chemical reactions =		4,645,000

Thus, much more heat is generated in the basic process, but more is required because a large amount is aborbed by melting the additions of lime to form the basic slag, and also there is greater radiation because the blows are longer and the operation is slower.

Comparison of Acid and Basic Bessemer.—The basic Bessemer

process finds its chief field in localities where the ores produce a pig iron very high in phosphorus, as, for instance, the Minette ores smelted in Germany and elsewhere. Germany is the great domain of the basic Bessemer process, as shown in Table XIX on page 153. The great skill of the Germans enables them to produce by this means a high grade of structural steel by a process which is not intrinsically as well adapted to improve the quality of the metal as any of the others, because of the greater oxidation of the bath, the danger of rephosphorization, and the liabilities to error in the "after-blow." England too is a large user of this process, but it is no longer in use in America because this country does not produce the desired grade of pig iron in sufficiently large quantities. We must have as much as 1.75 per cent. of phosphorus in the pig iron or the metal will give a cold blow, and this pig iron must be obtainable at a cheap price or else the process is not commercial. The operating costs are high for several reasons: (1) the blows are long; (2) the basic lining is more costly than silica and wears out faster; (3) fluxes must be added to form the slag; (4) the mechanical handling is more complicated, due to the extra pouring off of slag, etc. The slag is a by-product as a fertilizer, but the farmers have to be educated to use it, which has proven slow and difficult in this country.

VI

THE OPEN-HEARTH OR SIEMENS-MARTIN PROCESS

Open-hearth Plant.

The different open-hearth cycles are as follows:

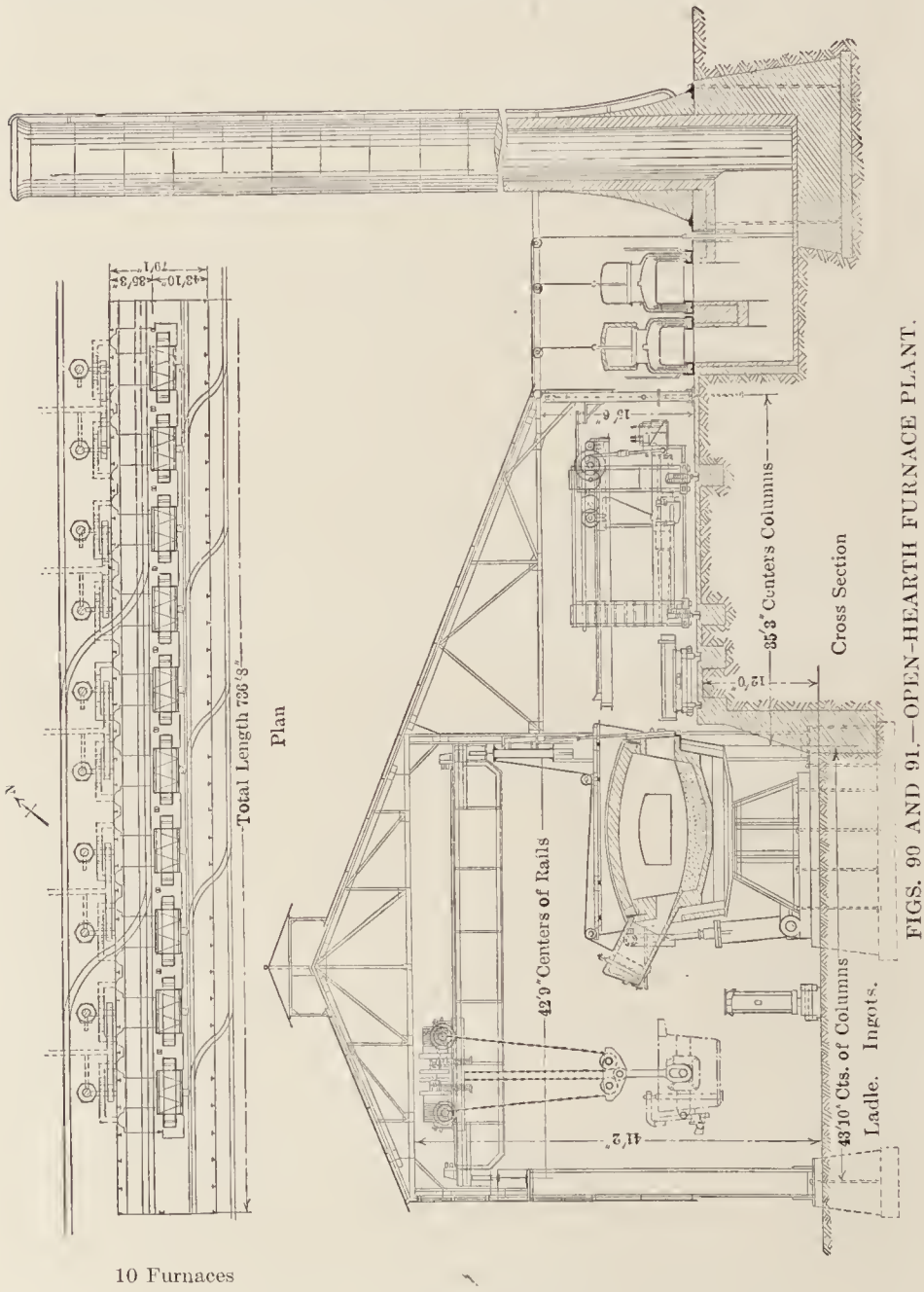
1. Getting the stock to, and in, the furnace.
2. Supplying the furnace with fuel and air and preheating both of these.
3. Working the charge, repairing the furnace, etc.
4. Recarburizing.
5. Disposing of the steel and slag.
6. Repairing and preparing ladles, ingot molds, etc.

A plan and elevation of a typical open-hearth plant is shown in Figs. 90 and 91. It is not to be presumed that all plants are laid out in the same manner, but that shown is a modern type which is much favored in America. The furnaces are arranged in a long single row, and with the level of the hearth several feet above the general ground-level of the plant.

Melting Platform.—On the same level as the hearth, and in front of the furnace, is the melting platform, or working platform, upon which are placed one or more charging machines, depending upon the number of furnaces to be served, running upon tracks extending the entire length of the working platform. The space above this is usually spanned by one or more electric traveling cranes which assist in repairs to the charging machines, in handling materials on the melting platform, and in pouring molten pig iron into the furnace where such practice prevails. The melting platform has a small extension around the back of the furnace to afford access to the tap-hole and the ladle into which the steel is poured, and for putting the recarburizer into this ladle when necessary. Upon the working platform are the valve handles for regulating the admission of gas and air to the furnace and for reversing the current of these at the proper time.

Gas Producers.—The gas producers are situated outside of the furnace house and in a long line parallel to it. This arrangement has the great disadvantage of placing the men on the working

platform between the smoke of the gas producers and the heat of the furnace, but there seems to be no good may of avoiding it. As the regenerators are usually placed underneath the working



FIGS. 90 AND 91.—OPEN-HEARTH FURNACE PLANT.

platform, this situation of the producers gives the least possible distance which the gas has to be carried, and therefore the least possible loss by deposition of tarry components.

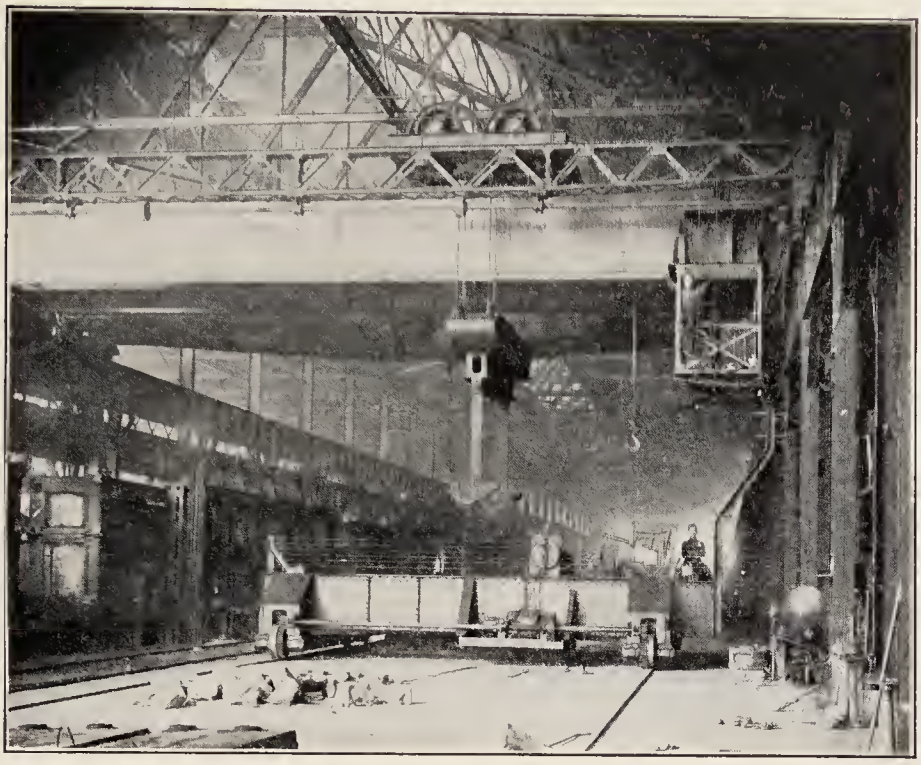
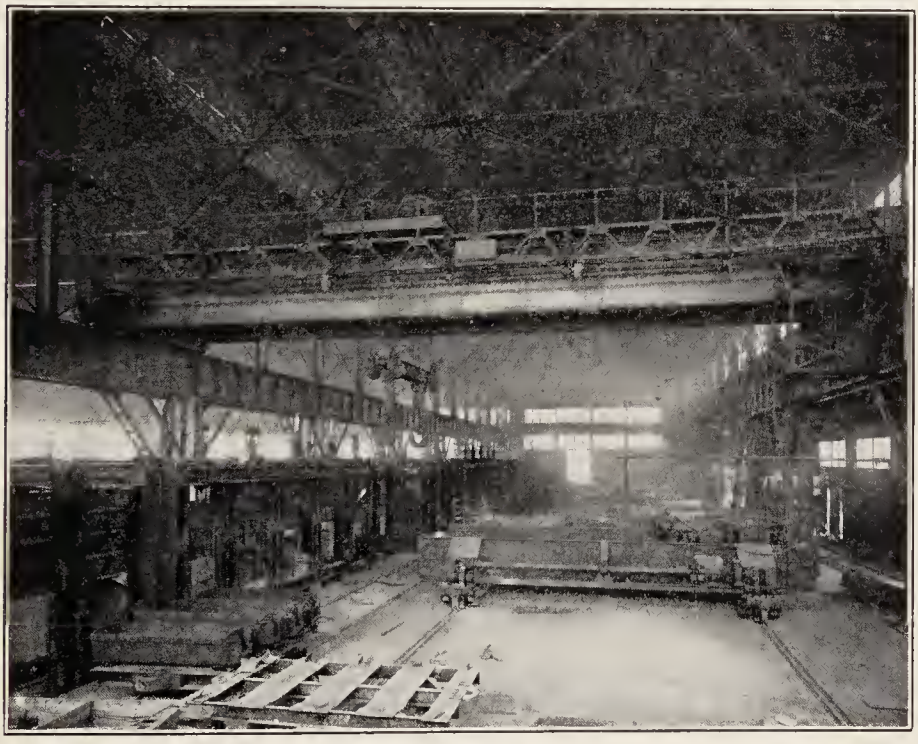


FIG. 92.—OPEN-HEARTH MELTING PLATFORM AND CHARGING MACHINE.



CHARGING BOXES.

FIG. 93.

Stock.—The stock yards are oftentimes placed between the furnace house and the gas producers, but this nearness is not necessary and stock is frequently stored by the end of the house, or even at some distance. For its transfer to the furnace, the stock is loaded into steel boxes similar to those in Fig. 93. Three or four boxes are supported on a little car, which is transferred in a train to the melting-floor, passing over a pair of scales on the way, where the weight is taken. Between the track of the charging machine and the line of furnaces runs the track upon which these cars are transferred, and if a constant supply of boxes is brought to the machine, it can empty them upon the hearth of the furnace at a rate of about 50 boxes (equivalent to about 125 tons) per hour.

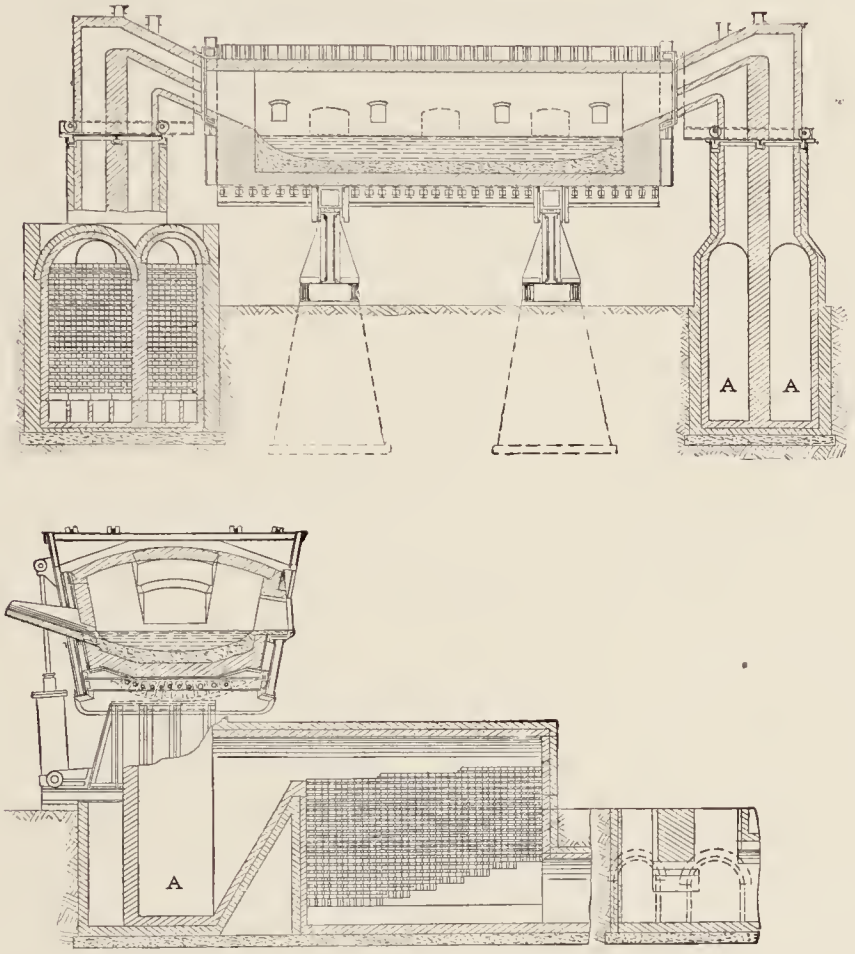
Casting-pit.—The casting-pit extends all the way behind the furnaces; it is on the general ground-level of the plant and therefore several feet below the melting platform. This pit is spanned by one or more electric traveling cranes of large capacity, which are used to hold the ladles while the steel is running into them from the tap-hole of the furnace and while it is being teemed into the ingot molds. They are also used to serve the pit for several purposes, such as carrying away the slag, transferring empty ladles to and from the point where they are lined and dried, etc.

Open-hearth Furnace

The form of a modern 75-ton open-hearth furnace is shown in Figs. 94 to 95. It consists of a long shallow hearth suitably enclosed in fire-brick and bound together with steel. A rolling furnace is shown in Figs. 90 and 91. There are many more stationary than tilting furnaces, but the general principles of the steel-making operation are the same in both.

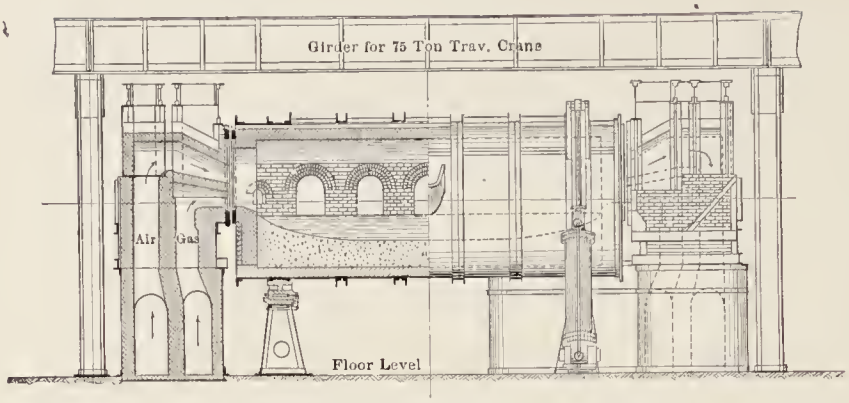
Regenerators.—With the furnace are connected two pair of regenerators which preheat the gas and air for combustion as described on page 49. The internal volume of each of these chambers is equal to 3/5 to 9/10 of that of the working-chamber itself. The larger the regenerators the greater will be the amount of heat intercepted in them, and therefore the lower the temperature of the gases that go to the stack. The amount of space actually occupied by the bricks, or checkerwork, is the important consideration, however, and this should be from 150 to 350 cu. ft., total, for all four regenerators per ton of furnace capacity, the

volume of the two gas regenerators usually being about 0.3 to 0.4 less than that of the air regenerators, because the volume of gas used is less than that of the air, and also because the gas does not require to be preheated so much, since it is already somewhat warm from the gas producer. During the operation of the furnace more or less slag, dirt, and dust are carried over with the

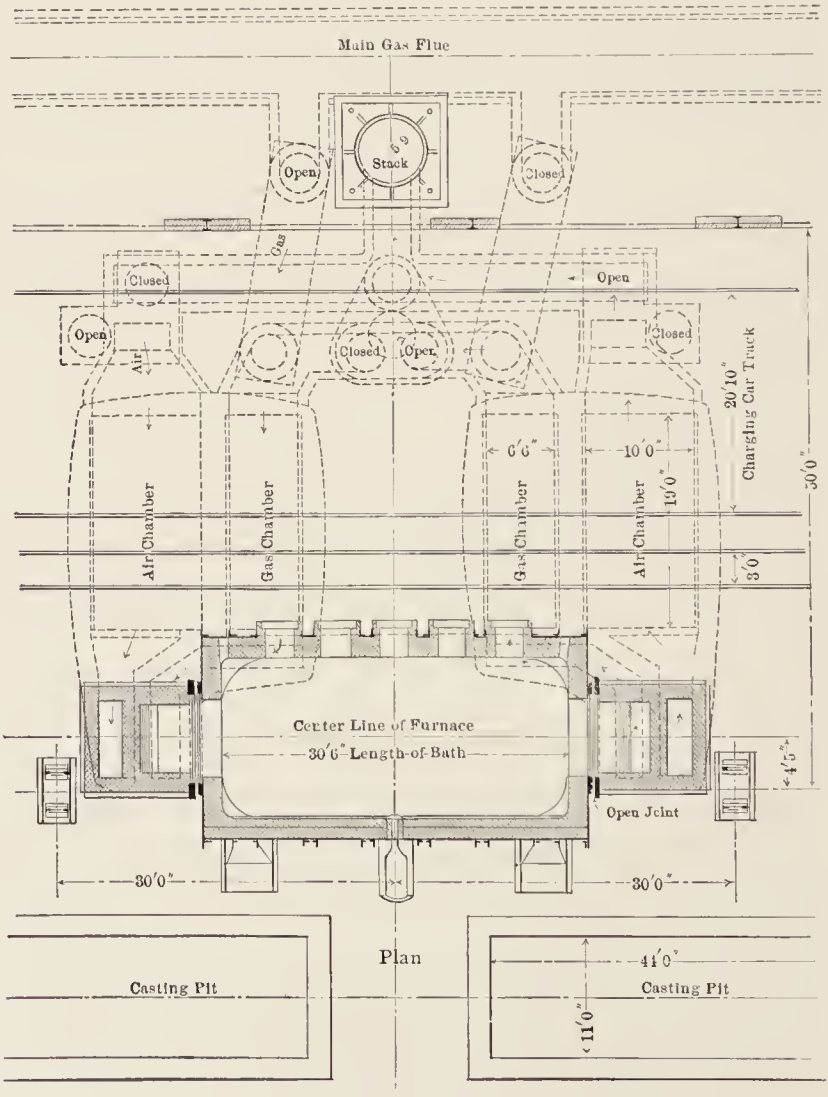


FIGS. 94 AND 95.
Longitudinal Section and Elevation.

outgoing gases. To intercept this the slag-pockets or dirt-pockets *A A* (Fig. 95) are provided; but in spite of them the space between the bricks of the checkerwork become partially choked, and for this reason, as well as because the deposit of dust makes the surface of the bricks rough, the total area between the bricks must be much larger than the area of the ports, so that the velocity of the gas will not be lessened. The furnace must be



Longitudinal Section and Elevation



FIGS. 96 AND 97.

laid off for repairs when the passages between the bricks are chocked by dirt, but, on the other hand, the interstitial space is limited, because the bricks must be laid in such a way that the maximum amount of surface shall be exposed and the gases forced to the greatest possible contact with them. Recent German improvements in regenerators include the use of bricks of special shape that will not become clogged. The checkerwork with such arrangements will last 2000 to 2500 heats.[1] The modern construction makes the regenerators as tall as possible in order that incoming gas and air may be forced into the furnace by the draught, and also because this chimney effect causes the incoming gas and air to naturally seek the hottest places and the out-going gas to naturally seek the coolest places, in this way equalizing the temperature in the different parts of the regenerators. They should be not less than 15 to 20 ft. high.

The space underneath the checkerwork should be so large that the incoming gas and air will distribute itself nearly uniformly through the different passages, and the temperature of the fire-bricks at this lower part will be, say, 400° C. (752° F.), although varying, of course, at different furnaces and at different times. When the regenerator is receiving the waste gas from the furnace, the temperature of these bricks will be that of the gases that go to the chimney, say 400° to 600° C., and when the air or gas is passing through the regenerator on its way to the furnace, these bricks will be somewhat cooler, depending upon the length of time that the regenerator has been in this phase of the operation. The temperature of the bricks at the top of the regenerator will be about 1000° C. (1832° F.), and therefore the air and gas entering the furnace will be the same.

Valves.—The reversing valves of the open-hearth furnace are a cause of large loss in producer gas, and sometimes the leak amounts to 10 or 20 per cent. Ordinary leaks may be prevented by having water-sealed valves, but sometimes the pressure of gas reaches the point where it overcomes the water pressure and escapes, causing a heavy loss. Moreover, water-sealed valves are open to serious objections: (1) The water may freeze, causing an endless amount of annoyance and trouble; (2) some water on the inside of the valve is vaporized and the vapor carried into the regenerator or into the furnace, where it absorbs heat; (3) the hoods are liable to warp with the heat; and (4) valves of this type

[1] See *Iron Age*, Aug 25, 1910, p. 436.

are so heavy that elaborate mechanism is necessary to reverse them. The common butterfly valves burn out rapidly and warp badly. If water-sealed, the hoods warp and leak. Lining the hoods with brick makes additional weight for shifting and adds very largely to the repairs. The mushroom type requires eight valves to a furnace and an elaborate arrangement for reversing them properly. They burn out badly unless water-cooled, when difficulty is met with from freezing (See Chap. XIX for cuts).

Ports.—The ports are so arranged that the flame shall be deflected away from the roof and yet not impinge upon the bath, or impinge only very slightly, because the bath would thereby be

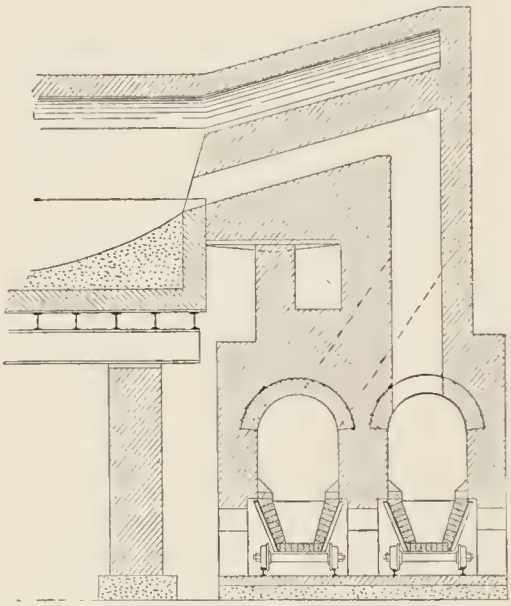


FIG. 98.—REMOVABLE BUGGIES TO CATCH SLAG IN SLAG POCKETS.

oxidized excessively. The gas should be spread out all over the width of the hearth beneath the air, and the two should be brought together just before they enter the laboratory, or work-chamber. The air especially must be kept away from direct contact with the bath, and for this reason the gas-ports are placed below the air-ports, which arrangement has the further advantage of promoting a better mixing of the two, since the gas is lighter and therefore rises. In America the favorite arrangement is two gas-ports, above which is situated a long slit, extending almost the entire width of the furnace, which serves as an air-port. This is not universal practice, however, for in some cases there are two, or even three, air-ports. In one case the

two gas-ports are built wide and low, so that they will deliver thin streams and get a better mixing of the two materials for combustion. The area of the air-port in a 50-ton furnace should be about 18 sq. ft., and the combined area of all the gas-ports on one end should be from 8 to 10 sq. ft., depending upon the quality of gas used.

The roof must be protected from the direct impact of the flame, because even the most refractory silica bricks would be melted by the intense heat. The chimney effect of the regenerators and uptakes gives the gas and air a velocity which causes them to enter the furnace with some force, and the construction of the ports directs the steam in the desired manner. The mouths of the ports are gradually melted away by the intense heat of combustion of the outgoing gases, until they finally cease to serve this purpose and it is impossible to get the proper mixing and the proper kind of a flame in the laboratory of the furnace. The ports must then be repaired, else the temperature cannot be maintained.

The ports have to suffer the full temperature of the out-going furnace gases (flame), and it has recently become more common to equip this part of the furnace with a water circulating system to keep the brickwork cool, which materially increases its life. The floor of the ports of basic furnaces are now commonly covered with a layer of chrome ore—a neutral refractory material which will not be slagged either by acid or basic fluxes. This protects the silicious brickwork of the port from the basic slag which is carried up by the outgoing gases. A recent novelty is to have the ports capable of being removed and replaced bodily when worn out, like the bottom of a Bessemer converter.

Draught and Chimney.—The draught must be sufficient to catch the flame about in the middle of the laboratory and drag it out through the ports on the opposite side from which it entered without allowing it either to drop down and touch the bath (as this is to be heated almost altogether by radiation) or to impinge upon the roof. This draught also has to do the work of overcoming the friction of the outgoing regenerators and flues. Its force will depend upon the height of the chimney and the temperature of the products of combustion after they have left the regenerators, which should be about 400° C. (752° F.), though even better economy (i.e., a lower temperature) than this is obtained in many cases. All the heat carried away by these flue gases is of

course wasted, but the great cost of the refractory bricks in the regenerative chambers makes it unwise to reduce the temperature of the flue gases too much by enlarging the checkerwork. The calculation of the amount of draught produced by any given height of chimney with any given temperature of flue gases, according to the method of Professor J. W. Richards, is given in Table XVII.

Roof.—The roof is made very thin and of the most refractory bricks that can be obtained, i.e., almost pure silica, with only enough lime to hold it together in a compact mass. The side walls are also thin, and the radiation from the furnace chamber is great, but this has to be endured, as thicker walls and roof produce endless trouble by expansion and contraction. The roof is arched and suspended from beams independent of the side walls.

TABLE XVII.—CALCULATION OF DRAUGHT OF CHIMNEYS.

The draught in a chimney is produeed by the gases within it being lighter than the air outside, and this lightness is due to their being hotter. In this ealeulation we assume the following data:

Data assumed:

- Air weighs 1.20 oz. per eu. ft. at 0° C. and 760 mm. pressure;
- Chimney gases weigh 1.03 times air at 0° C. and 760 mm. pressure;
- Water weighs 772 times air;
- Mereury weighs 13.6 times water;
- The friction of a chimney absorbs the equivalent of 0.1 in. of water on a water-guage showing draught, for every 100 ft. height of ehmney.

As the gases rise in the ehimney they eool; therefore their average temperature will be about 50° C. eooler than their temperature at the foot of the ehimney. Call this average temperature T° C. Then:

$$1.29 \text{ oz.} \times 1.03 \times \frac{273^\circ \text{ C.}}{T^\circ \text{ C.} + 273^\circ \text{ C.}} = \text{the weight of a eu. ft. of the ehimney gases at the temperature T° C.}$$

Subtraet this weight from 1.29 oz. and we get the differenee in weight of air and the furnace gases at the temperature T° C. Then:

Height of ehimney × differenee in weight = ounees draught pressure per square foot of ehimney area.

$$\frac{\text{Ounees draught} \times 12 \text{ in.}}{1.29 \text{ oz.} \times 772} = \text{equivalent height of water-gauge.}$$

From the height of a water-guage so found, we must subtraet the amount lost by frietion, or 0.1 in. × height of ehimney ÷ 100.

For furhter modifieations of this type of caleulation see No. 53, Part I, pp. 164, 166, 194, 200, and 201.

Life of the Furnace.—The "life" of an open-hearth furnace means the number of heats that it can make continuously without stopping for any more extensive repairs than can be made in the usual week's-end shut-down—i.e., without allowing it to cool down. No figure can be given for this except in the most general way. The life of the furnace will be ended usually in one of three ways: (1) The falling in of the roof, (2) the eating way of the ports, so that the flame can no longer be maintained properly, or (3) the giving out of the regenerators, which may occur either through the choking of the checkerwork, or through a crevice formed by the contraction and expansion of the bricks, so that there is a serious leak between the gas-chamber and the air-chamber, and premature combustion takes place. If a basic furnace makes 350 heats, it is considered good work, and we may perhaps tentatively consider this figure as the "three-score years and ten" of a furnace making steel for structural work and similar purposes. Water-cooled furnaces, and furnaces having greater length—40 ft. and over—will last nearly twice as long. Three hundred and fifty heats would mean about 18 to 24 weeks' work in America. An acid furnace will last about 1,000 heats. Foundry furnaces will only last about one-half as many heats as given above in many instances. The reasons for this are the higher temperatures usually attained when making steel for castings, and the longer heats. Many steel foundries only take two heats per day from their open-hearth furnaces.

Construction of Hearth and Bottom.—The hearth is made with a thickness of 18 to 24 in. inside the furnace shell, in the form of a shallow dish whose sides reach up to the level of the charging doors, and so constructed that the depth of the metal will be from 12 to 24 in.—the former figure in the case of a very small furnace, say 5 to 15 tons, and the latter in the case of one of 50-ton capacity. If the bath is too shallow the oxidation will be excessive and the wear of the lining by oxide of iron, with consequent production of slag, will be great;[1] if the bath is too deep, the melting and oxidation will be slow. In the case of an acid bottom, that portion of the lining next to the shell will be made up of refractory clay brick, and the upper portion will be formed by shoveling in silica sand, spreading it out in a thin layer about 1/2 in. thick over the entire hearth, and then allowing it to sinter at the full heat of

[1] In an open-hearth furnace the lining suffers the greatest wear at the side of the bath where the bath is thin, because the oxidation of the metal is the greatest there.

the furnace for about 10 minutes, so as to set it firmly in place. Upon this layer will be set another layer in like manner, until the whole hearth is constructed, and then it will be "washed" with a melted bath of old slag to fill up all crevices and give a glazed surface.

In the case of the basic hearth, the bottom is made of calcined magnesite, held together with 10 per cent. or less of anhydrous tar. In this case the layer of brick next to the lining is very thin and the magnesite and tar are set in in layers by the heat of the

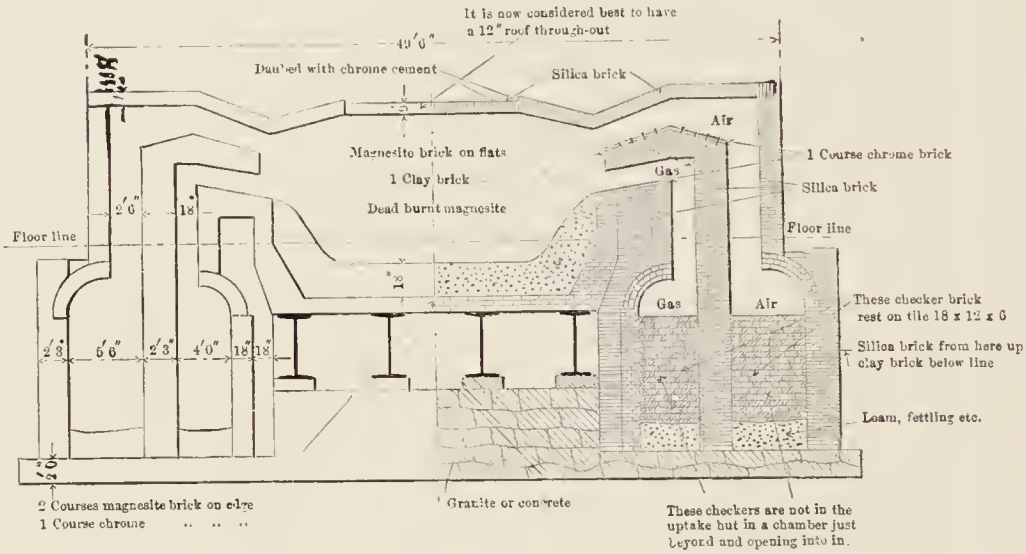


FIG 99.—MATERIALS OF CONSTRUCTION AND LINING FOR BASIC OPEN-HEARTH FURNACE.

furnace as in the case of the acid lining. The tar burns to a strong coke, which holds the mass together in a firm hard form. In some cases no tar is used, and the calcined magnesite is fritted slightly to hold it together; in other cases 15 per cent. of old slag is used as a bond. Pure magnesite gives a more permanent lining than dolomite,[1] and is now much used since its longer life more than compensates for its greater expense. Even when magnesite is used for the bottom, the topmost layer, or working bottom, and the repairs, or "fettling," put in during the intervals of the furnace life, are made of dolomite, because this sets more quickly. As the sides and roof even of the basic furnace are made of silica bricks, it is customary, although not absolutely necessary, to put a layer of neutral material between these bricks

[1] Dolomite is a magnesia limestone, and after calcining consists of a mixture of lime and magnesite (CaO, MgO), with a little silica and other impurities.

and the basic hearth, and also to protect this joint from excessive heat. The neutral material commonly used is chromite bricks, which are made of ground chromite (FeO, Cr_2O_3), held together with tar and then burned to form a firm, hard mass.

Repairing Bottoms.—Between the heats, bottoms are repaired by filling up holes with acid or basic material, as the case may be, and by more extensive attention at the end of the week. In this way the bottom may be made to last almost indefinitely, unless a part of the charge works its way down a crevice and forces up whole sections of the bottom lining, which not infrequently happens; while sometimes the charge even works its way out through the bottom of the furnace. A sticky or viscous slag is also liable to bring the bottom up by sticking to it. In the

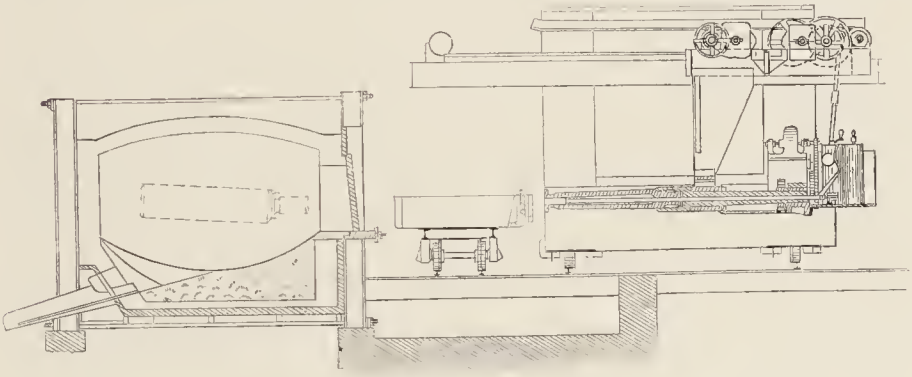


FIG. 100.

tilting furnace, the bottom may be repaired along the point where the worst corrosion usually takes place—i.e., at the edge of slag line—during the operation, by tipping the furnace until this place is uncovered.

Tap-hole.—In the stationary furnace, the tap-hole is made according to the section in Fig. 100. This is closed by material rammed into it from the door of the furnace. It sets quickly into a solid mass, which is pierced with a pointed bar when it is desired to allow the metal to run out. After tapping, the hole must be entirely freed from metal, and then it is made up and filled anew, ready for the next operation. This always delays work to some extent, and occasionally the tap-hole causes trouble by the charge working through it prematurely, or, on the other hand, by its becoming so hard that a hole is pierced in it only

after a long delay and much difficulty during which the oxidation continues in the charge beyond the desired point. In the tilting furnace there is no tap-hole, strictly speaking, but the opening into the metal-spout is closed by loose material, which is scraped away before the furnace is tipped to pour the charge.

Tilting Compared with Stationary Furnaces.—Tilting or rolling furnaces are more expensive to install than stationary ones, and require repairs to the machinery and power to operate them. They also require special arrangements of ports and uptakes, to be described later, and means for cooling the junction between the movable and stationary parts of the furnace. Their advantages are that they do away with troubles and delays from the tap-hole, the slag can be poured off at any time, and the charge may be tapped at a moment's notice, which is especially advantageous when making steels within very narrow limits of composition. One can also tap a part of the charge when using a rolling furnace. Furthermore, the back-wall of the bottom may be repaired more easily between heats when the furnace itself is still white hot. In the stationary furnace the angle of this back-wall will be about 60° or 70° from the horizontal, and loose material thrown in from the front doors will not rest on this angle; but the tilting furnace can be tipped until the back-wall is more nearly horizontal, and then loose material will remain upon it until sintered into place. The tilting type is of more advantage in the basic process than in the acid, because it enables the slag to be poured off at will, which is occasionally advantageous in basic practice. Except for foundry work, it is now unusual to install tilting or rolling furnaces. Foundry furnaces are generally small in size; 15 to 30 tons capacity is a common limit, and individual furnaces run as low as 5 or even 3 tons. These furnaces are most often charged by hand, and the rolling type facilitates this operation somewhat. The ease of tapping is an especial advantage where castings are being made, because delays may cool the metal to the point where castings will not run readily, or the carbon may be burned out excessively and the metal lack fluidity on this account. In that special type of practice known as the Talbot Process, which will be discussed shortly, a rolling furnace is essential because a part of the charge must be poured out of the furnace without removing all.

Tilting Furnaces.—There are two types of tilting furnaces, known respectively as the Campbell and the Wellman. In the

Campbell type the hearth of the furnace is arranged so that the center of tilting is coincident with the center of the ports, and therefore the furnace can be oscillated without shutting off the supply of gas and air. In order to facilitate this, there is a little clearance between the uptake and the furnace proper, and these parts are surrounded by water-cooled castings. In the Wellman type the gas and air supply must be cut off when the furnace is tilted. In tipping the Wellman furnace the ports move with the hearth, and they are therefore seated in a water-tank, which

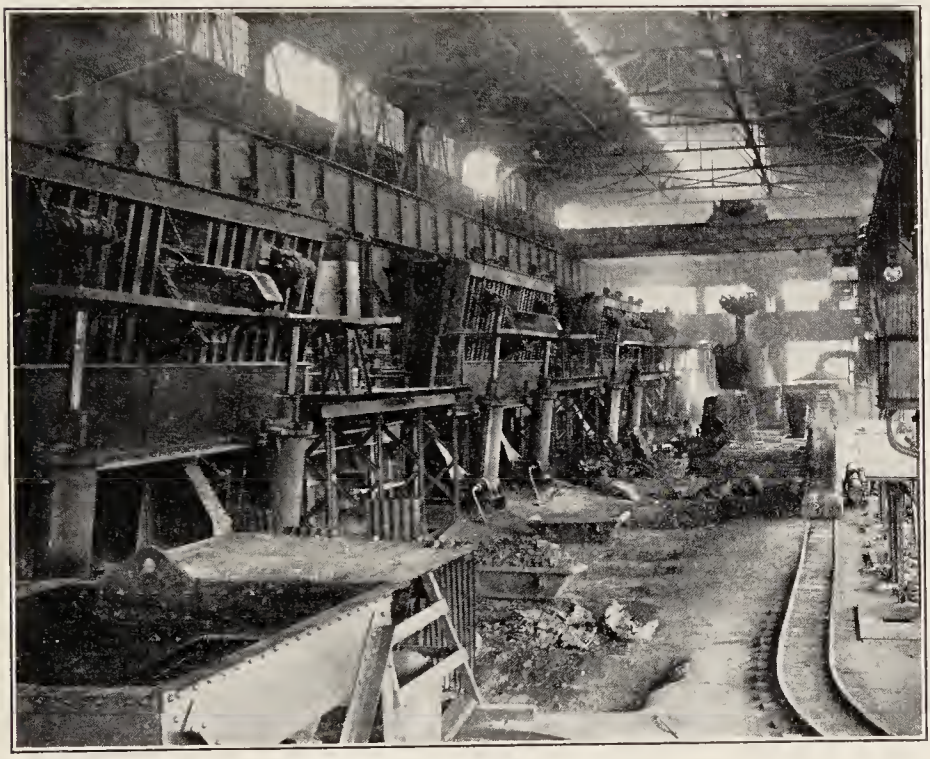


FIG. 101.—TILTING FURNACE.

makes an air-tight connection with the regenerators when the furnace is in a horizontal position, but breaks it when it is tipped forward.

The Wellman type is not as expensive to build as the Campbell, and probably requires less repairs. The Campbell type has the advantage that the bottom can be repaired along the slag line without interrupting the operation, and that the lining can be sintered into place by the heat of the flame when the hearth is in any position. This is more important in the acid furnace than in

the basic, where the mixture of dolomite and tar can be set by the heat contained in the furnace walls themselves. In the Wellman type, when the furnace is tipped for pouring, cold air can

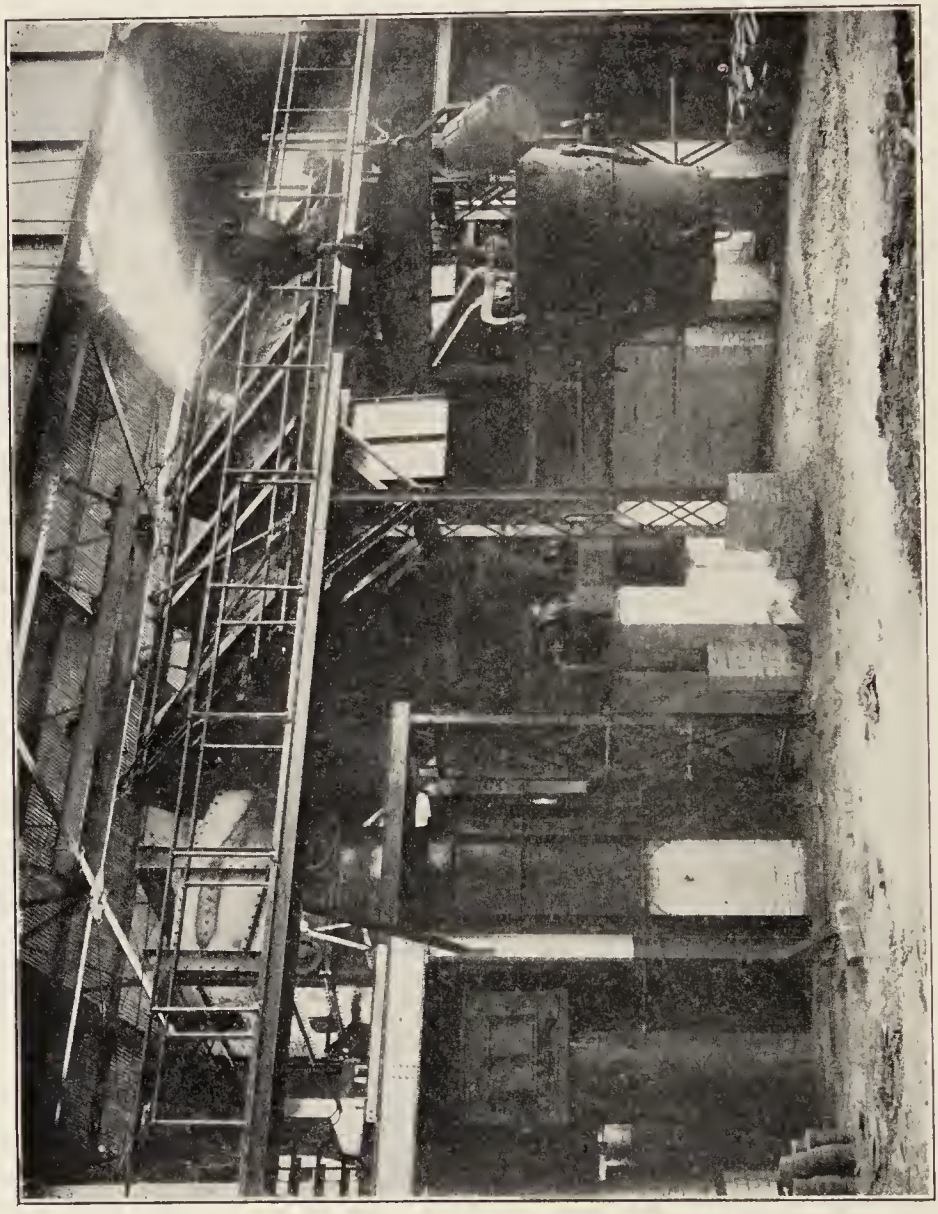


FIG. 102.—TAPPING AND POURING RECARBURIZER IN.

enter it through the port-holes, and may oxidize the manganese in the final product after recarburizing. Finally, a great advantage of the Campbell type is the fact that a great deal of ore can be used during the operation, and although the boiling of the charge

is violent on this account, metal does not flow out of the furnace doors, because the hearth can be tipped in the opposite direction. The slag which runs off during this period is allowed to pass through a hole in the bottom of the port-opening, at the joint between the fixed and the rotating portion, where it is continually exposed to the flame and therefore not liable to chill up.

Temperature.—There is almost no limit to the temperature attainable in the open-hearth furnace by frequent reversing of the valves, except the danger of melting the roof. The temperature is controlled by the intervals of reversing, and by throttling the amount of gas and air admitted to the furnace. It is the almost universal practice to reverse the valves every twenty minutes, in order to maintain a uniform temperature of the regenerators. The melter endeavors to keep the charge always in a very liquid state, and at the same time to have a slight excess of air, in order that the atmosphere of the furnace may be slightly oxidizing to burn the impurities in the metal. Every excess of oxygen, however, causes a loss of heat, because each volume of oxygen in the air is accompanied by four volumes of nitrogen, which carries heat out of the furnace, but does not assist in any way in the reactions. The actual temperature of the furnace will depend upon the length to which the decarburization is carried, because as the metal gets lower and lower in carbon, it requires a higher heat to keep it fluid. It will average about 1600° to 1700° C. (2912° to 3092° F.).

Fuel.—The amount of fuel burned per ton of steel made will depend not only on the quality of fuel, and skill of the operator of the furnace, as well as that of the gas-producer man when this type of fuel is used, but it will also depend on the length of the heats and the temperature desired for the product. The more impure the metal being converted the longer will be the heats; the greater the degree of purification, the longer the heats. For example, if we purify a charge consisting chiefly of pig iron, and remove all but traces of the phosphorus, and most of the carbon, it will take longer than to melt a charge of 20 per cent. pig with 80 per cent. of steel scrap and leave 0.70 per cent. of carbon in the steel. Furthermore, low-carbon steel must be delivered hotter than high-carbon steel in order to have the necessary fluidity. The more fluxes we have to melt, the greater the amount of heat to to be supplied, etc. The average fuel consumption when using producer gas will probably be between 400 and 800 lb. of coal

per ton of steel made for ingot steel—and this includes the small amount of gas used for preheating ladles, etc.—and 600 to 1000 lb. per ton for castings. Natural gas in the Pittsburgh district for ingots will average between 5000 and 6000 cu. ft. per ton of steel. The amount of fuel oil used will be within limits of 35 to 55 gallons per ton of steel. Good foundry practice making two heats of steel per day will use not much over 40 gallons per ton.

Size of Open-hearth Furnace.—The so-called "standard" open-hearth furnace has a capacity of 50 tons. The bath in such a furnace will have a length of about 30 to 35 ft., a width of about 12 to 15 ft., and a maximum depth of about 24 in. In America, however, there is now a tendency to increase the size to a capacity of 80 or even 100 tons. The result is a much better opportunity for complete combustion within the laboratory of the furnace, and therefore less deferred combustion as the gases escape through the ports and downtakes. This lengthens the life of the ports and promotes fuel economy.

The smallest practicable size of an open-hearth furnace is about 15 tons, and this is very expensive to operate. There are furnaces, however, as small as 5 tons capacity, but this is not good practice, even under the special circumstances which alone justify the use of the 15-ton furnace. The maximum practical size will not be far above 75 tons, and the real governing factor is the ability of the mechanical apparatus to handle the raw material and the product, besides which it is difficult to cast so much metal out of one ladle without having the casting temperature of the first metal too hot, or else that of the last metal too cold.

Basic Open-hearth Practice

Formerly, the open-hearth practice was divided into two types, known respectively as the "pig-and-ore process" and the pig-and-scrap process." In the pig-and-ore process the charge consisted entirely of pig iron, and the oxidation was hastened by the addition of as much ore as the charge would stand without boiling over; in the pig-and-scrap process the charge consisted of pig iron with large amounts of steel scrap, the proportion of the latter being so large in some cases that the operation became a mere remelting process, there being only enough pig iron for its silicon, manganese and carbon to protect the metal from excessive oxi-

dation. At the present time normal charges consist of pig iron and steel scrap, in proportions determined by financial considerations, and the operation is hastened by judicious additions of ore. The amount of steel scrap will vary all the way from 0 to 90 per cent., and will average not far from 50 per cent. in America. By decreasing the proportion of impurities in the raw material in the charge the scrap enables the process to be completed in less time.

It might seem as if the use of molten pig iron direct from the blast furnace, or through the medium of a mixer, might be as advantageous in open hearth practice as in Bessemer; but this is not quite so, because the metal in the open-hearth is subjected to oxidation at the same time that it is being melted, so that charging molten material does not shorten the operation as much. The time and labor cost for charging is less, but this advantage is partly neutralized by the scorification and wear of the hearth produced by the inpouring stream of melted metal. About one-half the open-hearth steel of America is made from molten pig. Where it is used the limestone is charged first, on top of that the steel scrap and any other cold metal, and finally the molten metal is poured in. In this way the hearth is protected as much as possible from being cut, and splashing against sides and roof, which would occur if solid pieces were dropped into liquid metal, avoided.

Pig and Ore Process.—Where pig iron is cheaper than scrap, the charge may consist entirely of pig and ore and it is then customary to hasten the operations by some of the special processes, such as the Talbot, the Monel, the Hoesch, etc. These conditions prevail in Germany, and there is occasionally practised the charging of molten pig iron from the blast furnace together with a fairly large proportion of ore. The working down of such a charge is shown in the Table XVIII.

Such a charge, however, must be under 1 per cent. phosphorus at the start, or the carbon will be gone before the phosphorus and the operation be much delayed by "pigging up." The ore should be charged first and the molten metal poured upon it. After approximately half the time of the heat is past, about one-half the slag is removed, carrying with it the bulk of the phosphorus and sulphur. The interposition of a mixer between the blast furnace and the open-hearth furnace gives a greater uniformity in the analysis of pig iron supplied to the open hearth, and also

TABLE XVIII

Charge: 49,385 lb. molten pig iron; 12,345 lb. ore; 3 to 4 per cent. lime between 1:45 and 5:00

Time	Analysis of metal					Analysis of slag				Remarks
	C	Mn	P	Si	S	SiO_2	FeO	MnO	P_2O_5	
12.45.....	3.61	2.32	0.67	1.890	0.044	.....	.....	.....	.....	Additions finished.
1.45.....	2.72	0.038	0.005	0.500	0.030	20.99	33.25	10.86	7.33	Warm and boils.
2.15.....	2.45	0.046	0.035	0.050	0.030	20.98	33.70	11.00	7.30	Begins to foam.
2.45.....	2.34	0.046	0.027	0.031	0.028	21.15	30.14	11.29	6.96	Warm and foaming.
3.15.....	1.94	0.054	0.020	0.042	0.026	22.35	24.47	11.68	7.59	Foams and is colder.
3.45.....	1.76	0.061	0.040	0.065	0.026	23.66	19.02	11.91	7.81	Foams and is colder.
4.15.....	1.68	0.084	0.044	0.033	0.030	23.83	15.57	12.24	7.95	Foams and is colder.
4.45.....	1.17	0.154	0.065	0.053	0.026	24.55	11.12	12.19	7.40	Cold.
5.00.....	1.14	0.199	0.094	0.035	0.034	25.76	9.57	11.80	7.21	Warmer and boils.
5.15.....	0.82	0.261	0.140	0.017	0.028	.....	.....	.....	.....	
5.45.....	0.71	0.307	0.138	0.015	0.028	22.67	7.44	10.43	6.41	Warmer and boils, 880 lb ore.
6.00.....	0.61	0.192	0.051	0.031	0.040	21.32	11.46	9.67	5.43	Warmer and boils.
6.20.....	0.375	0.253	0.019	0.015	0.036	22.56	9.90	9.28	6.89	Warmer and boils. 880 lb ore.
7.00.....	0.09	0.261	0.059	0.010	0.030	21.87	10.57	8.38	6.30	Carbon low enough.
7.15.....	0.084	0.269	0.035	0.020	0.038	21.17	10.34	7.95	6.21	353 lb. ferro-manganese.
7.30.....	0.089	0.499	0.067	0.004	0.042	20.29	9.45	9.24	5.73	Steel.

enables some sulphur to be removed in the mixer. In some cases the mixer is used as a preliminary refiner, about 4 to 5 per cent. of ore, and 5 to 6 per cent. of lime being added to it. In the mixer, manganese, silicon, phosphorus and sulphur are thus removed in amounts worthy of consideration. Purifying in the mixer increases the output of the open-hearth furnace; moreover, the costs for repairs, labor and fluxes in the mixer are comparatively small.

All-scrap Process.—In certain localities in America, steel scrap is cheaper than pig iron, but its use is open to the objection that it is severely oxidized and wasted during the melting period unless there be some pig iron with it to give a reducing influence. Instead of using as much pig iron, however, some plants now partly replace it with a carbonaceous material which is a by-product of petroleum refining, and is known as "carbo." This "carbo" is an impure form of carbon which dissolves readily in the steel and serves the purpose of a reducing influence.

Normal Pig and Scrap Process. Order of Charging.—In the pig and scrap process using about 50 per cent. of each, the order of charging for a 75-ton furnace is as follows: about 6,000 lb. of small steel scrap is spread evenly over the bottom, preference being given to plate scrap because of its greater covering power. On top of this is charged from 12,000 to 16,000 lb. of lime and about 8,000 lb. of ore or scale. Then follows about 70,000 lb. of scrap and 30,000 lb. of pig iron. After about 2 hours the heat of the furnace has softened this charge so that it has sunk in the furnace and there is room for the final charge consisting of some 12,000 lb. of scrap and 60,000 lb. of pig.

Composition of Pig Iron Used.—Basic pig should be free from adhering sand, and therefore only machine-cast metal will ordinarily be used, or else that cast in metal molds. Its silicon should be below 1 per cent., and its manganese above 1 per cent., though the price of manganese ore makes this ingredient an expensive luxury. It is desired because it makes the slag more fluid and aids in removing sulphur. The phosphorus will be almost any figure up to 2 per cent., but a regular supply of pig with more phosphorus than that would tempt the manager toward the basic Bessemer process. Silicon and phosphorus increase the amount of slag, lengthen the operation, and require lime to flux them.[1]

[1] Analysis of Basic Pig Iron in Table, p. 8.

Fluxes.—The function of the basic lining is to remain inert and serve simply as a container for the bath. In order that the slag may be at all times rich in lime (35 to 45 per cent. CaO ordinarily), from 5 to 30 per cent. of lime is added with the pig and scrap, the exact amount depending upon the impurities in the metal charged. Especially if the charge is high in sulphur, the slag must be kept as rich in lime as possible without making it too infusible and therefore viscous, the limit being about 55 per cent. CaO. The lime is usually added in the form of calcined limestone, and, as already noted, the higher the silicon and phosphorus in the metal the greater must be the amount of lime used. It is also customary to charge ore with the pig and scrap, in order to increase the amount of oxidation that takes place during the melting period. This ore has very little effect on the basic lining, although it would rapidly corrode a silicous one. Further additions of ore are made during the operation if necessary. The average total amount of ore added to a 50-ton charge will be between 1/8 of a ton and 2 1/2 tons, equal to 0.25 to 5 per cent.

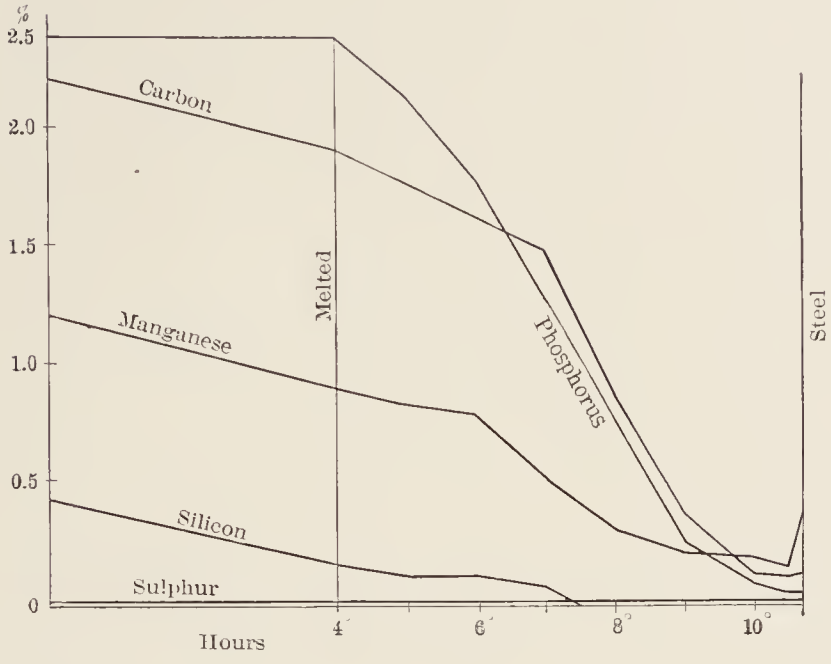
Chemistry.—It takes about 4 or 5 hours for the charge to melt down level, and during that time the silicon is almost entirely eliminated, while the proportion of carbon and manganese is somewhat reduced, as shown by Figs. 103 and 104, which also show the chemical changes that take place during the entire operation. These reactions must be controlled by the melter, because it is necessary that the carbon shall be eliminated last, and therefore it is occasionally necessary to "pig up" the charge, i.e., add pig iron in order to increase the amount of carbon. On the other hand, in case the phosphorus is being eliminated very fast, the oxidation of the carbon may be hastened by "oreing down," as it is called, i.e., adding ore to produce the reaction.

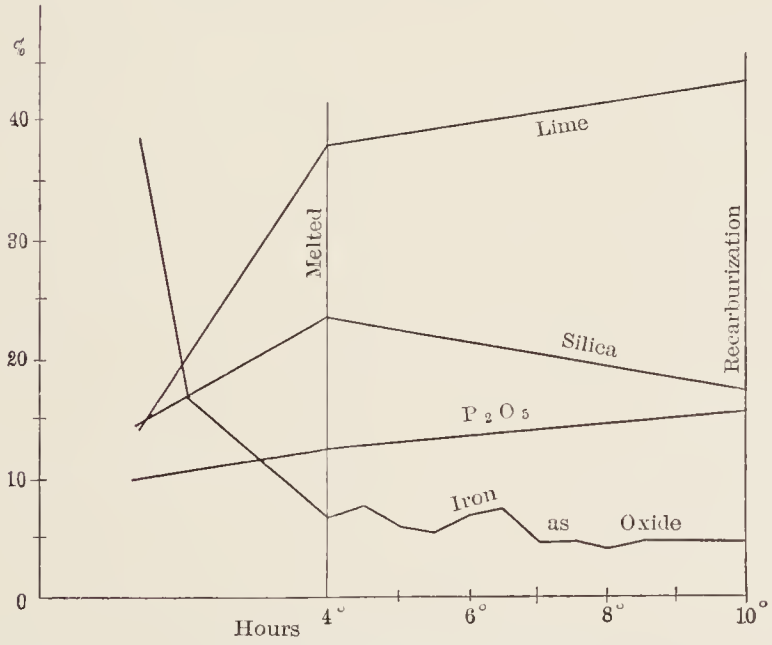
$$Fe_2O_3 + 3C = 2Fe + 3CO.$$

If the carbon is eliminated before the phosphorus, a great deal of iron will be oxidized, because the phosphorus does not protect it as much as the carbon.

When the charge is entirely melted,[1] and at intervals thereafter, the melter takes a spoon-ladle full of metal and pours it into an iron mold. As soon as this is set hard it is cooled in water, and

[1] The charge is not entirely melted until the lime has come up, which takes place about 2 hours after the charge has melted down level.





FIGS. 103 AND 104.—CHEMICAL CHANGES IN BATH AND SLAG IN A BASIC OPEN-HEARTH FURNACE.

from the appearance of its fracture the melter can estimate very closely the amount of carbon and phosphorus it contains. In many plants it is customary to tap heats on these estimates alone and astonishing accuracy can be obtained by these methods as to the amount of carbon contained in the bath of steel. In all large plants, however, the laboratory analysis is made for phosphorus and usually for carbon as well, and these determinations may be made in 20 minutes or less.

Functions of the Slag.—The functions of the slag are: (1) To absorb and retain the impurities in the metal, particularly silicon, manganese and phosphorus, and as much sulphur as possible; (2) to lie upon the top of the bath as a blanket and protect it from excessive oxidation by the furnace gases; and (3) to oxidize the impurities of the bath by means of its dissolved iron oxide, which comes chiefly from ore, scale, etc., added by the "melter."

For the retention of phosphorus and sulphur, the slag must be rich in bases. For the oxidizing it is necessary that the slag shall be fluid, so that it will mix easily with the bath, and therefore the content of lime must not be too high. During the boil, when the carbon is passing off, there is an intimate mixture of metal and slag, and there is even such a violent agitation of the bath that the metal itself is frequently uncovered in places and exposed to direct oxidation by the furnace gases.

The removal of sulphur is a variable quantity and cannot be altogether depended upon, but there is usually a large loss of this element during the operation, in spite of slight additions of sulphur from the coal through the gas. This sulphur reduction is greatly assisted if the slag is thinned out (i.e., its melting-point reduced) by the addition of calcium fluoride (CaF_2) just before the end of the operation. The higher the slag is in lime, provided it remains at the same time fluid, the more complete in general will be the sulphur elimination, but over 55 per cent. of lime usually makes the slag viscous, unless the calcium be added in the form of fluoride, or of chloride ($CaCl_2$). The latter agent was added in many cases by the recommendations of E. H. Saniter, but the practice was never general in the United States, and the use of calcium fluoride (known as fluorspar) answers most purposes, unless the sulphur in the charge is excessive. Manganese assists in sulphur removal by forming MnS. The sulphur in this is slowly oxidized and the manganese returns to the metal.

It is of importance that the final slag in the open-hearth

operation shall be a nonoxidizing one, lest the metal itself be full of oxide and very "wild," i.e., give off gas abundantly during solidification. Therefore for the best quality no ore should be added within one hour of the finish of the operation.

Melting Low Carbon Steel.—When steel for purposes requiring dead soft metal is made, the charge is calculated so that it will melt practically dephosphorized and of the desired carbon. In other words, very little oxidization goes on after the lime is up. Large amounts of scrap are used, and the necessary amount of ore to take care of the phosphorus, is put in with the charge.

Slag.—Final basic slags will contain:

10 to 15 per cent. SiO_2
45 to 55 per cent. $CaO + MgO$
10 to 18 per cent. FeO
5 to 15 per cent. P_2O_5.

The slag is the crux of the open-hearth operation, and it must be kept slightly oxidizing at all times except just at the end. In the basic process it must be kept always strongly basic in order to retain phosphorus and sulphur and also spare the lining as much as possible. Sufficient lime must be added when necessary to maintain these conditions, but fluidity must not be destroyed or the slag will lose its power to react well upon the impurities, whose chief means of oxidation it is.

Weight of Slag.—The weight of slag will depend upon the silicon, phosphorus and dirt in the metal, and will average from 10 to 30 per cent. of the weight of steel. Since the slag takes practically all the lime charged into the furnace, its weight can be calculated with sufficient accuracy by the same formula given for calculating the blast-furnace slag: Divide the total lime (CaO) used with the charge (plus 30 per cent. of itself to allow for wear of the lining) by the percentage of lime in the slag.

Loss.—The weight of steel produced will be a variable proportion of the weight of metal charged, depending upon the amount of pig iron in the charge, the amount of ore used, the extent to which the carbon was eliminated before tapping, etc., but it will average perhaps 93 to 96 per cent., the difference being made up as follows, in a typical example:

ANALYSIS OF CHARGE

(50 per cent. pig; 50 per cent. scrap)

	Pig iron per cent.	Scrap per cent.	Average per cent.	Loss per cent.
Carbon	3.75	0.25	2.00	2.00
Silicon	0.70	0.06	0.38	0.38
Manganese	1.50	0.40	0.95	0.95
Phosphorus	1.30	0.04	0.67	0.67
Sulphur	0.37	0.03	0.20	0.20
20 per cent. slag @ 15 per. cent. Fe				3.00
				7.20
Iron reduced from ore				1.50% gain.
Net loss				5.70

Recarburizing.—Steel must not be recarburized in the presence of a basic slag, lest the carbon, silcon, and manganese of the recarburizer reduce phosphorus from the slag and cause it to pass back into the metal:

$$2(3CaO.P_2O_5)+5C=6CaO.P_2O_5+5CO+2P$$

$$4(3CaO.P_2O_5)+5Si=2(6CaO.P_2O_5)+5SiO_2+4P.$$

Therefore in basic practice the recarburizer is added to the stream of metal while it is pouring from the furnace into the ladle, and special arrangements are made for allowing the slag which floats on top of the metal to overflow at the top of the ladle and thus be gotten rid of in a large part. In careful practice "rephosphorization" need not exceed 0.01 to 0.02 per cent. of the steel, although a much larger increase may take place through accident.

The recarburizer usually consists of ferromanganese, together with anthracite coal, charcoal or coke which is broken into small pieces and loaded into paper bags. About 45 per cent. of the broken coke is burned and the other 55 per cent. will be dissolved by the steel. It is practically impossible to melt spiegeleisen in the cupola, because a cupola must be run continuously in order to do satisfactory work, while the open-hearth process is too slow and too irregular to use a continuous supply of molten recarburizer.

In making soft steel the carbon is reduced to about 0.10 or 0.15 per cent. in the bath, and then the necessary amount of recarburizer is added. In making high carbon steel, on the other hand, two methods are possible: We may reduce the bath to

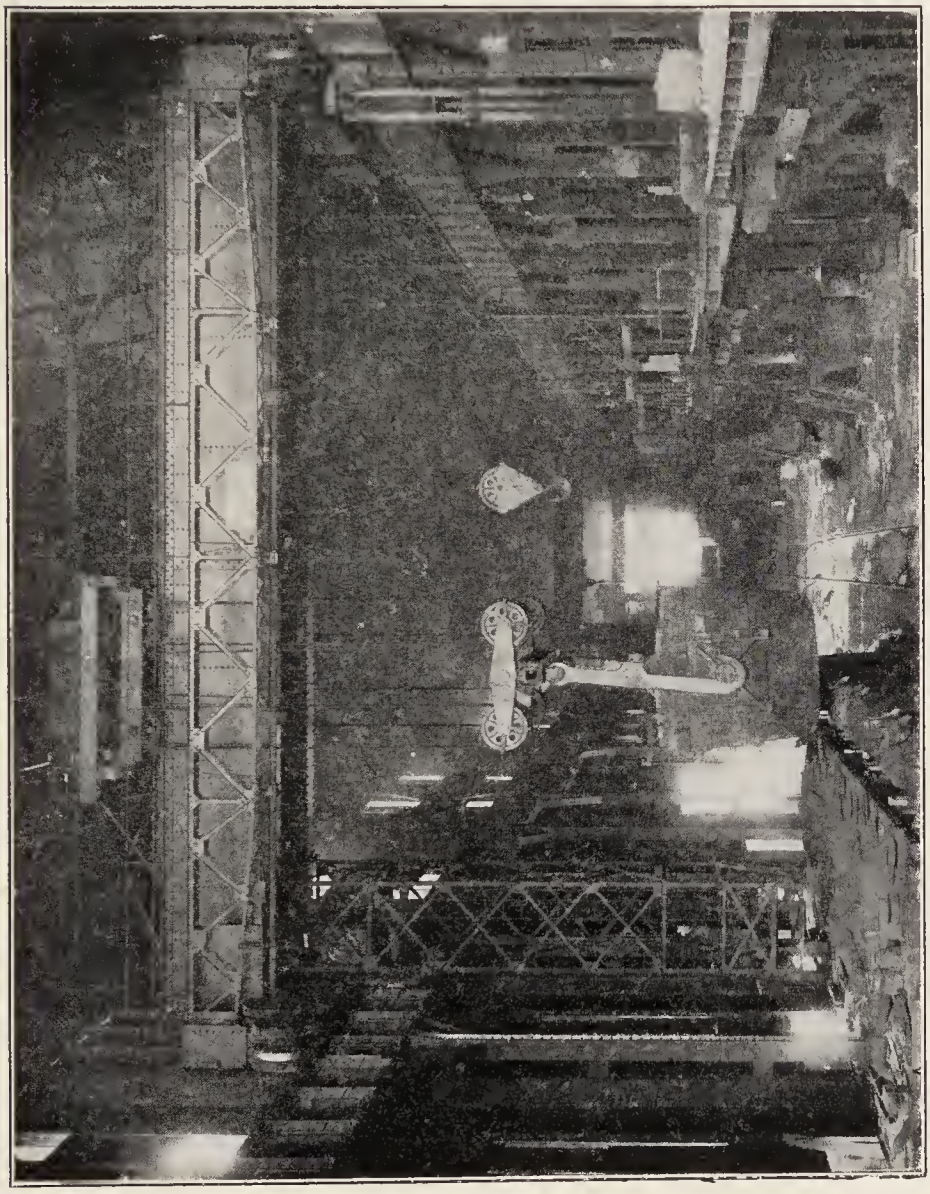


FIG. 105.—OPEN-HEARTH HEAT READY FOR TEEMING.

0.10 or 0.15 per cent. and then add sufficient recarburizer to bring the carbon up to the desired point, or we may bring the bath down to only slightly below the desired point and recarburize it to the desired percentage. The former practice usually

frees the steel more completely from gas and therefore makes it less wild, besides reducing the danger of phosphorus being left in the steel. It takes a longer time for the operation and more fuel.

Teeming Basic Steel.—R. A. Bull[1] gives the following figures showing the oxidation of silicon and manganese, and the enrichment in phosphorus and sulphur, by the slag during the teeming of a series of basic heats. The practice here exemplified is in

AFTER POURING	P	S	MN	SI	MINIMA AND MAXIMA PHOSPHORUS	SULPHUR	MANGANESE	SILICON
50%	.018	.020	.79	.34	1 2 3 4 5	2 3 4	5 6 7 8 9	2 3 4
89"	.024	.020	.75	.30				
93"	.027	.023	.74	.32				
96"	.026	.023	.73	.31				
100"	.031	.021	.73	.25				
50"	.018	.021	.82	.32	1 2 3 4 5	2 3 4	5 6 7 8 9	2 3 4
89"	.029	.024	.75	.26				
93"	.032	.024	.72	.26				
96"	.036	.024	.71	.26				
100"	.038	.027	.68	.24				
50"	.018	.018	.81	.38	1 2 3 4 5	2 3 4	5 6 7 8 9	2 3 4
89"	.024	.019	.72	.34				
93"	.024	.020	.68	.33				
96"	.026	.022	.66	.32				
100"	.031	.023	.58	.30				
50"	.028	.026	.82	.35	1 2 3 4 5	2 3 4	5 6 7 8 9	2 3 4
89"	.037	.028	.79	.33				
93"	.039	.028	.77	.31				
96"	.039	.028	.75	.31				
100"	.056	.029	.71	.21				
50"	.024	.025	.70	.25	1 2 3 4 5	2 3 4	5 6 7 8 9	2 3 4
89"	.035	.029	.63	.22				
93"	.038	.029	.61	.21				
96"	.042	.029	.59	.22				
100"	.046	.032	.57	.21				
50"	.015	.025	.78	.29	1 2 3 4 5	2 3 4	5 6 7 8 9	2 3 4
89"	.020	.026	.76	.24				
100"	.022	.027	.73	.22				
50"	.023	.026	.73	.33	1 2 3 4 5	2 3 4	5 6 7 8 9	2 3 4
89"	.034	.027	.71	.29				
100"	.044	.032	.70	.23				

FIG. 106.—PROGRESSIVE ANALYSIS OF A 50-TON BASIC OPEN-HEARTH HEAT

Note.—In "Minima and Maxima" figures for phosphorus and sulphur show hundredths per cent; figures for manganese and silicon show tenths per eent; the carbons remaining constant throughout are not shown.

making steel castings, so the time of teeming will be usually somewhat longer than when ingots are cast, and the effects studied will be correspondingly increased.

[1] The Foundry, September, 1909, page 34.

Acid Open-hearth Practice

Acid open-hearth practice is in many respects similar to basic, but the operations are shorter because: (1) a much larger proportion of steel scrap is commonly used; (2) phosphorus is not removed; and (3) no fluxes are added, except in rare instances, when a little silica is charged at the beginning to prevent iron oxide cutting the lining.

Chemistry.—The chemistry of the acid process is much simpler, because neither phosphorus nor sulphur is removed; therefore it is necessary to start with pig iron and scrap low in both of these elements. The progress of the operation is shown in Fig. 106. This amount of silicon in the charge will determine the amount of slag made, provided manganese is low; therefore low silicon pig iron is preferred.[2] The manganese is usually low also because: (1) this element is costly; (2) it increases the amount of slag made; (3) it forms a base which requires silica for fluxing it, thereby cutting the lining; and (4) it increases the waste, since all the manganese burned represents a loss in weight of metal purchased. The manganese, as well as the silicon, in the bath is usually reduced to only a trace by the time the charge is melted. H. H. Campbell has shown that the open-hearth slag at the end of the acid operation automatically adjusts itself to contain about 46 per cent. of bases (FeO + MnO), the remainder being principally silica, and that this ratio remains almost the same even when very varying amounts of iron oxide are added.

Melting for Mild Steel.—In America approximately one-third of the acid open-hearth steel made is used for castings containing most frequently not very far from 0.20 per cent. carbon. Structural steel, with about the same analysis in carbon, forms another large fraction of the annual tonnage. In this type of practice, the charge is so constituted of pig, scrap and ore that it will contain when melted, only traces of manganese and silicon, and not much more than 0.35 per cent. carbon. Where pig iron is cheaper than scrap, the carbon after melting may be higher than this, but this increases the length of the operation. The silicon should be all oxidized in order that the slag may be fully formed and cutting of the lining avoided. The analysis of the slag when melted is practically the same as at the end of the operation, provided it is always maintained in a fluid condition so it will

[2] See analysis of pig iron, page 8.

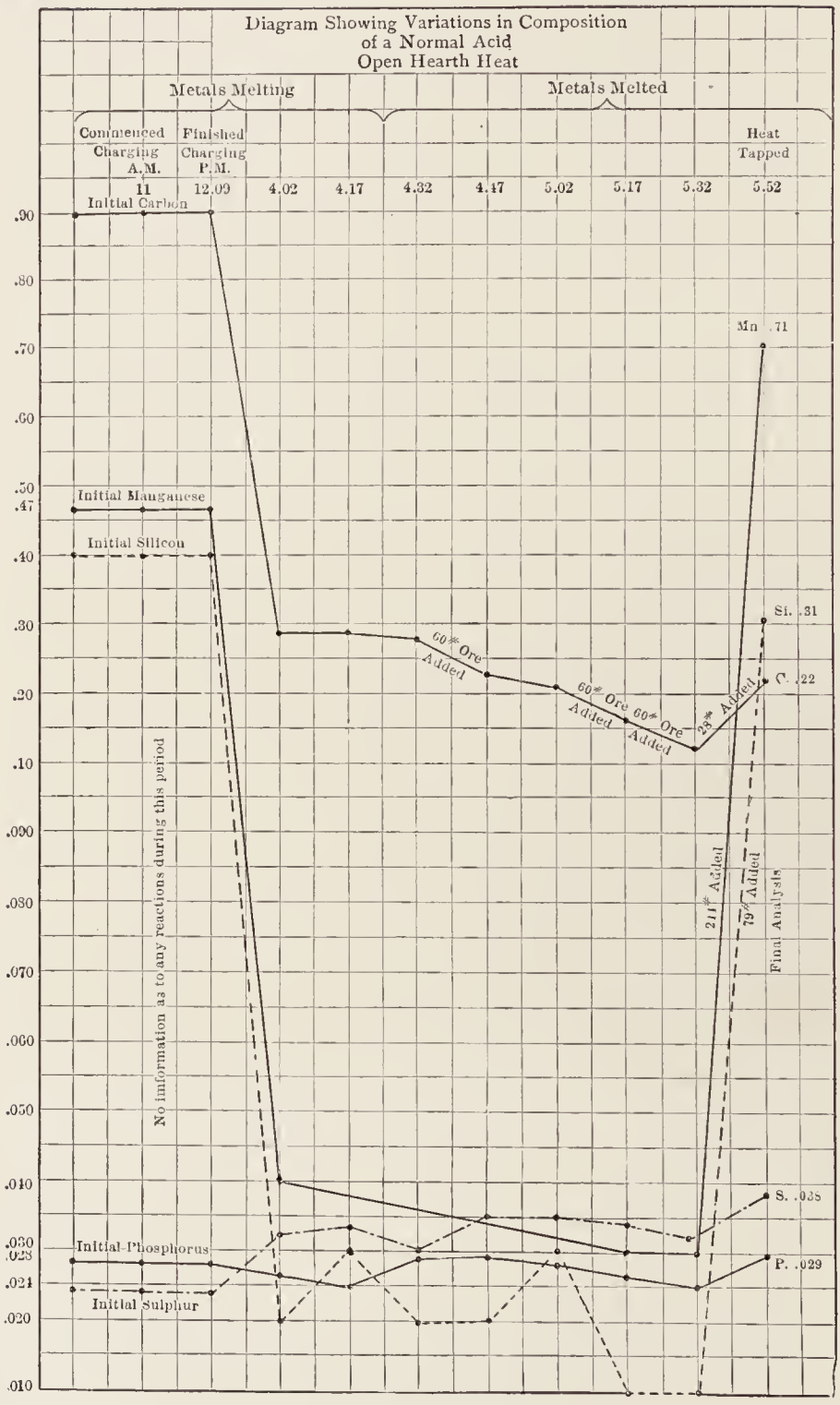


Diagram Showing Variations in Composition
of a Normal Acid
Open Hearth Heat
Metals Melting
Metals Melted
Commenced Charging A.M.
Finished Charging P.M.
Heat Tapped
11
12.09
4.02
4.17
4.32
4.47
5.02
5.17
5.32
5.52
Initial Carbon
Initial Manganese
Initial Silicon
Initial Phosphorus
Initial Sulphur
Mn .71
Si. .31
C. .22
S. .038
P. .029
60# Ore Added
60# Ore Added
60# Ore Added
60# Ore Added
23# Added
211# Added
79# Added
Final Analysis
No information as to any reactions during this period
.90
.80
.70
.60
.50
.47
.40
.30
.20
.10
.090
.080
.070
.060
.050
.040
.030
.028
.024
.020
.010

FIG. 106 A.

react rapidly with the carbon. Ore is added from time to time, but this is almost immediately reduced:

$$3C + Fe_2O_3 = 2Fe + 3CO$$
$$C + Fe_2O_3 = 2FeO + CO.$$

The amount of slag increases all the time, showing that the reduction of iron oxide is not complete, and that silica from the lining is constantly entering the slag to maintain a proportion of about 50 per cent. SiO_2. The slag also takes some oxygen from the furnace gases and transmits it to the carbon of the bath. At no time, however, when the charge is properly worked, is the slag long in a strongly oxidizing condition, in contra-distinction to the situation in the basic process. Recarburization more usually is affected while the metal is still in

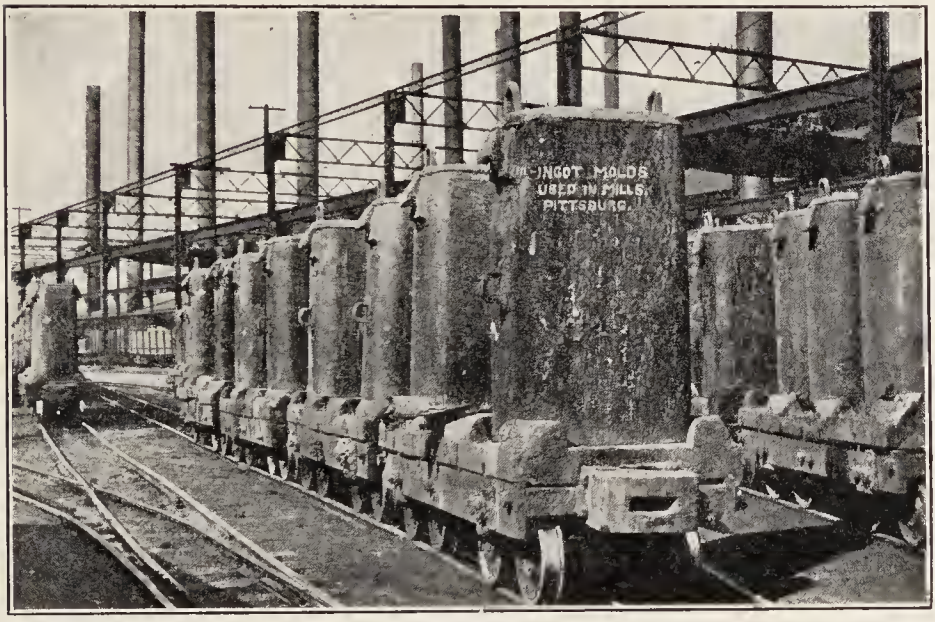


FIG. 107.

the furnace, because the objections to this practice obtaining in the basic process do not apply here, and there are certain advantages such as it being more readily melted; being stirred into the metal better during the transfer into the ladle, etc. On the other hand, a little manganese is oxidized and wasted.

Melting for High-carbon Steel.—When making steel for tires, springs, and other objects requiring higher carbon, two general types of practice are followed, depending to some extent upon the relative cost of pig iron and steel scrap. If scrap is cheap,

we may regulate the charge so as to melt a low-carbon bath, and then bring this up to the desired point by melting pigs of iron in it just before adding the ferro-manganese, etc. This has the advantage of insuring more thoroughly the removal of dissolved oxygen from the metal, but makes the final analysis a little more uncertain because a variable proportion of carbon is oxidized in the furnace during the melting period. The temperature of the furnace also affects this variable. The second type of practice is to melt to carbon only a little above the desired proportion, and then boil this down in the usual way. In either event the ferro-manganese and ferro-silicon are usually added in the furnace. Sometimes, as in the basic process, anthracite coal in bags is used instead of pig iron to bring up the carbon, the bags being thrown into the stream as it runs into the casting ladle from the furnace.

Loss.—The loss in the acid process will not be as large as in the basic, because the pig iron and scrap charged are not so impure, and because the amount of slag made and the amount of iron oxidized and retained by the slag are not so large. The loss will vary on an average from 3 to 5 per cent., so that the final metal will weigh 95 to 97 per cent. of the weight of the charge. The analysis of this difference is as shown below.

ANALYSIS OF CHARGE

(30 per cent. pig; 70 per cent. scrap)

	Pig iron per cent.	Scrap per cent.	Average per cent.	Loss per cent.
Carbon	3.75	0.25	1.30	1.30
Silicon	0.90	0.10	0.34	0.34
Manganese	0.60	0.40	0.46	0.46
Phosphorus	0.035	0.045	0.04	0.00
Sulphur	0.03	0.03	0.03	0.00
8 per cent. slag @ 22 per cent. Fe =				1.76
Net loss				3.86

Weight of Slag.—The weight of slag made in the acid process may be determined, according to the method of H. H. Campbell,[1]

[1] See page 275 of No. 2. Old edition.

from the total amount of manganese in the furnace, which will include that put in with the charge (including any that may have been in the ore) and that added with the recarburizing. First we subtract from this total the amount of manganese in the metal tapped; the weight of the remainder is then divided by the percentage of the manganese in the slag, which gives the weight of the slag. The amount of acid slag will depend primarily upon the amount of silicon in the charge and will vary on the average from 6 to 18 per cent. of the weight of the metal charged, about three-fourths of which is formed during the melting period.[1]

Coal Burned.—The amount of fuel used per ton of steel made in the acid open-hearth furnace will be perhaps 50 to 100 lb. less than in the basic furnace, but will depend again upon many varying conditions, so that figures should be used only with caution. (See pages 127 and 128).

Special Open-hearth Processes

The original pig-and-ore process is abandoned very largely in America, because of the length of time required to burn off the impurities unless they are diluted by steel, and because steel scrap is more abundant than it is in Europe. It is difficult for a novice to understand why the reactions are not more rapid in the open-hearth furnace, when the entire purification of pig iron in the puddling-furnace is accomplished in an hour and a half, including melting; but the difference is due to the very shallow bath in the puddling operation and its extensive contact with the fettling. If we should attempt to purify under such strong oxidizing conditions in the open-hearth furnace, the molten metal would boil violently, because of the high temperature, and for the same reason would also become so charged with oxygen as to be worthless. Even at the low temperature of the puddling-furnace, the boiling is so violent as to increase the height of the bath, and this action would be proportionately increased at the temperature of the open-hearth furnace, which, at the end of an operation producing dead-soft steel, will be about 1650° to 1700° C. (3002° to 3092° F). The increase in volume of the metal when carbon monoxide gas is escaping from it may be likened to that of champagne when the drawing of the cork allows a rapid escape of gas. There is another reason why the boil causes more of an increase

[1] In the case of making structural steel (say 0.18 per cent. carbon).

in the volume of the bath in the open-hearth furnace than in the puddling-furnace: in the latter, the carbon monoxide has only molten metal and slag to bubble through, but in the open-hearth process, where cold ore is added to the charge, it produces a certain amount of chilling of the metal and slag adjacent to it, and the gas having to bubble through this somewhat pasty material causes a greater increase in its bulk. By the time the puddling charge becomes pasty, the carbon is largely gone and therefore there is not a violent action.

Various attempts have been made by different metallurgists to adapt the open-hearth process to the use of all pig iron rapidly oxidized by iron ore or other agencies, and this has led to the Talbot and the Monell processes, each of which is carried on in a single furnace, molten pig iron being acted upon by a highly oxidized liquid slag, formed prior to the addition of the pig iron in the Talbot process and coincident with it in the Monell process. It has also led to the Duplex process, whereby a large proportion of the oxidation is effected in an acid Bessemer converter, the operation being completed on a basic hearth. The ingenuity of the German manufacturers has also enabled them to use the process in a slightly revised form, as already described.

Duplex Process.—In several large American plants the combined Bessemer and basic open-hearth process is in operation, an acid converter being used to oxidize the silicon, manganese, and most of the carbon, while the phosphorus and the remainder of the carbon is eliminated in a basic open-hearth furnace. In the different localities there are different ways of carrying out this combination, but these divide themselves into two general methods: In one method, the metal is blown in the converter until it is purified to the point where it is practically equivalent to so much high-phosphorus, molten steel scrap, which is then mixed with either liquid or solid pig iron in the open-hearth furnace and worked as any ordinary pig-and-scrap heat after melting. In another, and more common, method, the pig iron is blown in the converter until it contains about 1 per cent. or so of carbon, and this product, with little or no additional pig iron, is then dephosphorized and decarbonized in the open hearth furnace. The advantages of the combined process are: it shortens the open-hearth purification by sometimes much more than half the usual period; it relieves the basic hearth of the presence of silica which tends to scorify it. Both of these improvements have a

secondary advantage in increasing the life of the hearth. An advantage from the Bessemer standpoint is that a poorer grade of iron can be converted and yet a higher grade of steel produced. Open-hearth railroad rails, which are frequently made by the Duplex process in America, bring $2 per ton more than Bessemer rails. Finally, the Duplex process makes the steel-maker independent of the variable price of so-called "melting steel scrap."

In carrying out the process, large mixers with capacities of 250 and even 750 tons each are used as a reservoir for the liquid pig iron: sometimes a little purification is carried on in these furnaces. They supply pig iron to the converters, and to basic furnaces as well, if desired. The blown metal is also frequently poured into a mixer of its own, which serves as a source of supply to the open-hearth furnaces, and again a little purification may be effected in this mixer. The use of these mixers not only makes each part of the process somewhat independent of delays in the other part, but also corrects slight irregularities in analysis of pig iron or blown metal, thus providing more uniform conditions in each furnace, which greatly facilitates the operation therein. Under proper conditions, an open-hearth furnace with auxiliary converter and mixers, may make as many as 40 to 50 heats per week, as compared with 18 heats by the ordinary method. In one large American plant, the Duplex process is employed in connection with Talbot open-hearth furnaces, which are described in the following section.

The name "Duplex process" is also given to a combination of Bessemer or open-hearth furnaces with electric "super-purifiers," but this practice will be discussed under the head of electric processes.

Talbot Process.—The Talbot process has a basic lining and contains a charge above 200 tons in some cases, as, for example, at the Jones & Laughlin plant, in Pittsburg, Pa. As the bath of metal is over 3 ft. deep, however, which is about twice that of an ordinary bath, the furnace is only as large in other dimensions as a 100-ton furnace. The tilting furnace is commonly used in order that any desired quantity of metal or slag may be poured out at will. The operation is continuous and the furnace is drained of metal only once a week. After the first charge has been worked down to the desired percentage of carbon, the great part of the slag is poured off, and then about one-third of the steel is poured into the ladle, recarburized, and teemed into the

ingot molds in the usual way. To the charge of metal left in the bath is now added iron ore and limestone to produce a basic and highly oxidized slag, and through this slag is then poured an amount of pig iron equal to the steel removed. The reaction between the impurities in the pig iron and the iron oxide in the slag is very vigorous, but does not cause a frothing or foaming, because all the materials are in the liquid form and the gas bubbles through them without great difficulty;—however much of the slag runs out of the furnace.

The oxidation is so rapid that the silicon and manganese are said to be oxidized almost immediately, together with most of the phosphorus; then the carbon is worked off in the usual way, using more ore and limestone, if necessary. The temperature is low at first, in order that the phosphorus may be more readily burned. At the end of about three to six hours, the bath has again become purified, and another cast removed, the whole operation being then repeated. The yield of steel is 106 to 108 per cent. of the weight of the pig iron charged, because of the large amount of iron reduced from the ore by the impurities in the pig iron.

$3C + Fe_2O_3 = 2Fe + 3CO$ (absorbs 108,120 calories).
$6P + 5Fe_2O_3 = 10Fe + 3P_2O_5$ (evolves 117, 900 calories), et. al.

The advantages of the process are: We obtain three or four heats of 75 tons each in 24 hours without the use of steel scrap; the yeld is large (though this advantage is somewhat neutralized by the cost of the iron ore used); and the temperature of the final metal can be more easily controlled. The disadvantages of the process are: The very large cost of furnaces and the slightly higher cost for repairs.

Monell Process.—A. Monell, when metallurgist of the Carnegie Steel Company, developed a pig-and-ore process in which highly heated oxidizing and slag-making materials were made to react with the impurities in molten pig iron without the necessity of having a reservoir of metal into which to pour it. Upon a basic hearth he heats limestone and a relatively large amount of ore, or other form of iron oxide, until they become pasty, and then pours molten pig iron, equivalent to the capacity of the furnace, upon it. Oxide up to 25 per cent. of the weight of the pig iron charge is used. The temperature of the bath is necessarily low, since pig iron direct from a blast furnace or from a mixer will not be more than 200° or 300° C. above its melting-point, and therefore the phosphorus will be oxidized very rapidly. The slag

foams up and pours out of a special slag-notch; in an hour the bath is free from 90 per cent. of the phosphorus, most of the silicon and manganese, and all but about 2 per cent. of carbon. The operation is then continued in the usual way to eliminate the carbon, and the metal is tapped when this has been reduced to the desired point. The total time is the same as an ordinary pig and scrap process. The American rights to the process are owned by the Carnegie Steel Company and they are operating it at many of their furnaces. No details are known generally, but it is to be presumed that the results are favorable. The apparent disadvantages of the process are excessive cutting of the hearth and a heavy loss of iron in the rich slag which flows off at the beginning of the operation. The Monell process has been used successfully in England, with pig iron containing up to 2 per cent. of phosphorus.

Processes in Two Open-hearth Furnaces.—At a low temperature phosphorus is very easily oxidized and absorbed by a basic slag, even in the presence of carbon, but when the heat is high the oxidation of phosphorus is hindered by the carbon, for the reason already explained—that the affinity of carbon for oxygen increases more rapidly with the temperature than the affinity of the other elements in the bath. We could obtain the desired conditions in the open-hearth process, but the operation would be extremely slow at this low heat, and the carbon would pass away slowly. These difficulties have been met by the Campbell No. 2 and Bertrand-Thiel processes, the former of which was developed at Steelton, Pa., and the latter at Kladno, Bohemia.

Campbell No. 1 Process.—The pig-and-ore process using molten metal has long been in operation in the Campbell tilting furnace, and the frothing of the bath is taken care of by tipping the furnace backward so that no slag or metal will pour out of the door, though a large amount of the former flows from the slag-hole between the ends of the furnace and the ports. The operation is continued in this way for two or three hours, since, as already noted, the furnace can be tipped without cutting off the supply of gas and air, and the yield of steel is 104 to 106 per cent. of the pig iron charged.

Campbell No. 2 Process.—At the same plant there is also a combination process in which the charge, consisting of all pig iron, or of pig iron[1] and scrap, is placed in a basic open-hearth

[1] The pig iron charged may be either in the liquid or solid state.

furnace and the purification carried on at a low temperature until almost all the silicon and phosphorus and part of the sulphur and carbon are eliminated. The bath is then tapped from the basic furnace and poured into an acid-lined furnace, care being taken that none of the basic slag goes with it. At this period the metal is low in phosphorus and sulphur, and contains about the same amount of carbon that a cold charge would have contained as soon as melted. The conditions are therefore the same as if low-phosphorus low-sulphur material had been charged into an acid furnace and melted there, and the process is now continued at a higher temperature, in the usual way to make acid open-hearth steel. The disadvantage of this process is that the transferring of molten metal from one furnace to another is not an easy matter, nor, in fact, is it possible with the arrangements in many plants.

Bertrand-Thiel Process. Hoesch Modification.—The Hoesch process is now in use in some of the German plants, where it is said to give very satisfactory results. Instead of using two furnaces, as in the original Bertrand-Thiel process, and pouring from one to the other, it uses one furnace but pours the bath into a ladle after the first period of purification; the purpose of this is to separate it from the highly phosphorized slag; when this is effected, the metal is poured back into the same furnace and the purification completed. In the first period, all the silicon and manganese, most of the phosphorus and about one-half of the carbon, are removed; in the second period, the remaining phosphorus, carbon and some additional sulphur are eliminated. The slag separated after the first period contains 20 to 25 per cent. of P_2O_5, wherefore it finds a ready sale as agricultural fertilizer. The chemical history of a charge is given on p. 149.

Comparison of Purification Processes

Acid with Basic Open-hearth.—Acid open-hearth steel is believed by engineers to be better than basic, and is usually specified for all important parts of structures, although not so rigidly to-day as a few years ago. This is in spite of the fact that phosphorus and sulphur, two very harmful elements, are lower in the basic steel. The basic process is less expensive than the acid, because high phosphorus pig iron and scrap are cheap, and the lower cost of materials used more than balances the greater

WORKING OF A CHARGE BY THE HOESCH PROCESS.

Charge: 7853 lb. ore; 1697 lb. roll scale; 4144 lb. lime; 51,323 lb. pig from mixer

Time	Analysis of metal.—Per cent.					Analysis of slag.—Per cent.								
	C	P	Mn	Si	S	FeO	MnO	Al_2O_3	CaO	MgO	P_2O_5	S	SiO_2	
First Period:														
12.15	3.28	1.86	0.96	0.32	0.132	.....	.....	.....	.....	.....	.....	.....	.....	
1.10	2.47	0.59	0.17	Tr.	0.102	.....	.....	.....	.....	.....	.....	.....	.....	
1.30	1.90	0.47	0.22	Tr.	0.098	10.25	5.03	1.36	41.56	4.32	22.85	0.069	12.2	
1.40	1.65	0.37	0.22	Tr.	0.098	7.26	4.96	1.38	45.48	4.00	22.26	0.124	11.8	
2.05	1.46	0.26	0.34	Tr.	0.082	4.67	3.93	1.60	48.86	4.00	22.13	0.138	11.4	
	Charge: 4806 lb. ore; 2843 lb. lime; 11,931 lb. scrap.													
Second Period:														
3.50	0.38	0.09	0.29	Tr.	0.100	19.64	13.49	3.17	33.64	6.92	6.25	0.110	12.2	
4.10	0.20	0.05	0.23	Tr.	0.089	15.78	12.08	3.00	35.78	6.70	6.70	0.165	15.4	231 lb. oxide.
4.30	0.09	0.045	0.26	Tr.	0.090	15.83	8.88	2.32	43.88	6.00	5.50	0.289	13.2	806 lb. lime.
4.45	0.07	0.035	0.26	Tr.	0.080	14.13	10.19	2.21	43.79	6.10	5.57	0.206	14.2	
5.05	0.06	0.035	0.27	Tr.	0.078	16.23	8.32	2.20	45.30	5.90	5.55	0.275	14.0	440 lb. ferro-manganese.
5.10	0.04	0.03	0.25	Tr.	0.077	17.20	7.67	2.00	46.19	6.12	5.15	0.316	13.1	
5.15	0.08	0.04	0.47	Tr.	0.067	17.03	10.25	1.90	46.28	5.92	5.00	0.344	12.4	

As an average, 75 per cent. of pig and 25 per cent. of scrap is used in this process, and the yield is 104.42 per cent.

cost of the basic lining and the lime additions and the circumstance that the acid furnace has a higher output because the heats are shorter. Acid steel is preferred by many, however, for the following reasons:

(*a*) A basic slag will dissolve silicon from the metal; we therefore recarburize in the basic process by adding the recarburizer to the steel after it has left the furnace, instead of in the furnace, as we do in the acid process. Should any basic slag be carried over with the metal, however, which is liable to happen, there is the danger that the ingots will be too low in silicon. They are then impregnated with gas bubbles, or "blow holes." Indeed the last part of a heat of basic steel teemed from a ladle will be lower in silicon and manganese and higher in phosphorus and sulphur, as already indicated in discussing the basic process. A goodly proportion of the acid open-hearth steel made in America goes into steel castings, which receive no mechanical treatment before going into service. In such products, of course, the presence of blowholes is most harmful; hence the predominant use of the acid process, although this predominance in point of tonnage is now being lost. Even the acid Bessemer process, modified as explained under the chapter on Founding, gives a product for castings, which, from the viewpoint of freedom from blowholes, is preferred to the basic open-hearth.

(*b*) Moreover, the recarburizer does not mix with the steel as well if it is not added in the furnace, because of the stirring in pouring, and this sometimes produces irregularities.

(*c*) A basic slag is more highly oxidized than an acid slag; therefore the metal at the end of the operation is more highly charged with oxygen. For this reason we add a larger amount of manganese in the recarburizer, but the remedy is never quite as good as prevention.

(*d*) Since we cannot remove the phosphorus from the bath in the acid process, it is necessary to use only picked iron and scrap, whereas, in the basic process, good steel can be made from almost any quality of material. Many engineers believe, however, that a better grade of steel results from using the picked material.

(*e*) It occasionally happens in the basic process, after the phosphorus has all been oxidized in the slag and the operation is ended, a good deal may get back into the metal again. This is especially liable to happen when basic slag is carried over into the ladle before the recarburizer is all in. If this occurs, and if

the bath is very hot, a reaction may take place between the basic slag and the acid lining of the ladle. In this way the slag will be enriched in silica and phosphorus will be forced out of it into the metal (see p. 136).

Basic Open-hearth with Bessemer.—Basic open-hearth steel is better than Bessemer steel. The reasons for this are believed to be:

(*a*) The open-hearth process being slower, more attention and care can be given to each detail. This is particularly true of the ending of the process, for if the Bessemer process is continued only a second or so too long, the bath is highly charged with oxygen, to its detriment, and even under normal circumstances there is more oxygen in the metal at the end of the Bessemer process than at the end of the basic open-hearth, because there has been so intimate a mixture between metal and air.

(*b*) For the same reason the Bessemer metal is believed to contain more nitrogen and hydrogen,[1] which are thought to be deleterious.

(*c*) The heat of the Bessemer process is dependent upon the impurities in the pig iron, and especially upon the amount of the silicon, and can be controlled only to a limited extent by methods that are not perfect in their operation. Furthermore, the heat is regulated according to the judgment of the operator and his skill in estimating the temperature of the flame. Irregularities therefore result at times, and these produce an effect on the steel, because the temperature at which the ingots are cast should be neither too high nor too low. It is true that the temperature of the open-hearth steel is also regulated by the judgment of the operator, but more time is afforded for exercising this judgment and for controlling the heat.

(*d*) In the Bessemer process we get rid of all the carbon first, and then recarburize to the desired point. In the open-hearth process we may stop the operation at any desired amount of carbon, and then recarburize only a small amount. Therefore the open-hearth has the advantage of greater homogeneity when making high-carbon steel, since a very large amount of recarburizer may not distribute itself uniformly.

In order to produce the best quality of steel, it must be cast into ingot molds within a certain limited range of temperature, which varies according to the amount of carbon, etc., that it con-

[1] The hydrogen is said to come from the moisture in the blast.

tains. Therefore, in casting the very large heats of the open-hearth process, the ingots must be very large, else the first one will be too hot and the last one too cold for the best results. On the other hand, if the ingots are large, segregation is liable to be excessive (see page 166).

For over fifteen years the Bessemer process has been fighting a losing battle to maintain its supremacy against the inroads of the basic open-hearth, which have been possible because of the increasing cost of Bessemer pig iron, due to the exhaustion of the low phosphorus ores. The Bessemer process will probably be relegated in future to the place chiefly of an adjunct to the open-hearth or electric furnaces in the "Duplex processes," unless large bodies of Bessemer ores are discovered.

On account of its ability to make low carbon steel more readily than the basic open-hearth, the Bessemer process has a hold on the wire and welded steel-pipe industry, although even here the open-hearth process has encroached. For rolling very thin plates, for tinplate, etc., we want a metal relatively high in phosphorus, and therefore the Bessemer process is largely used here, although in some cases ferrophosphorus is being added to basic open-hearth metal to accomplish the same result. The reason phosphorus is desired is because the plates are rolled very thin by doubling them up and putting several thicknesses through the rolls at the same time. Low phosphorus metal welds together too much under these circumstances.

The chief requisites of railroad rails are lack of brittleness and ability to withstand wear. The Bessemer process is able to provide such a material, and it works so well in conjunction with the rapid, continuous operation of the rail-rolling mill that it has a decided advantage. It produces a small tonnage of ingots at frequent intervals (say 15 tons every 7 minutes), while the open-hearth process provides a large tonnage of ingots, which may come at irregular intervals and thus alternately delay and overcrowd the rail-mill operations. But notwithstanding these advantages, an increasing tonnage of basic open-hearth rails is made every year in the United States, and now the majority of rails of large sizes are made by the open-hearth process, in which we include the Bessemer-open-hearth Duplex process. The lower phosphorus in the basic steel enables us to get a tough rail with higher proportions of carbon, and this higher carbon gives a steel more resistant to wearing down by abrasion.

TABLE XIX.—STEEL PRODUCTION IN METRIC TONS,[1] 1910

	United States	Germany
Acid converter	9,563,376	171,108
Basic converter	.....	8,030,571
Total converter	9,563,376	8,047,679
Acid open-hearth	1,231,575	252,148
Basic open-hearth	15,537,006	5,125,421
Total open-hearth	16,768,581	5,377,569
Crucible	124,260	83,202
Electric, etc	56,220	36,158
Total	26,312,437	13,698,638

TABLE XX.—MAKE OF ACID AND BASIC STEEL, 1910

	Acid		Basic	
	Tons	Per cent.	Tons	Per cent.
United States	10,802,579	41	15,292,329	59
Germany	542,646	4	13,135,992	96
Total	11,345,245	.....	28,248,321	.....

Crucible Steel with Others.—Crucible steel is the most expensive of all and costs at least three times as much as the next in price—acid open-hearth steel. It is also the best quality of steel manufactured,[2] and for very severe service, such as the points and edges of cutting tools, the highest grades of springs, armor-piercing projectiles, etc., it should always be employed. The reason for its superiority is believed to be that it is manufactured in a vessel which excludes the air and furnace gases, and is therefore freer from oxygen, hydrogen and nitrogen. Perhaps the fact that the process is in some ways under a little better control than any of the others, and receives more care, on account of

[1] From "Mineral Industry."

[2] Except electrically purified steel, discussed in Chap. XVII.

being manufactured in small units, assists in raising its grade. Crucible steels are usually higher in carbon than Bessemer and open-hearth steels, because the special service to which the crucible steels are adapted is usually one requiring steel that can be hardened and tempered—for example, cutting tools, springs, etc., and only the high-carbon steels are capable of this hardening and tempering. This is not an essential characteristic of the product, but is most often the case.

Wrought Iron with Low-carbon Steel.—Wrought iron costs from 10 to 20 per cent. more than the cheapest steel. Its claim to superiority over dead-soft steel consists in its purity and the presence in it of slag. Just how much advantage the slag is has never been proven; it gives the metal a fibrous structure which, perhaps, increases its toughness and its resistance to breaking under bending or under a sudden blow or shock. Some think that the slag also assists in the welding of the material, but this is doubtful, and it is probable that the easy weldability of wrought iron is due alone to its being low in carbon. Some also believe that the slag assists the metal in resisting corrosion; hence one reason for the preference of some engineers for wrought-iron pipe for boilers and other purposes. An advantage of wrought iron in this connection is its rough surface to which paint or other protective coatings will adhere more firmly than to the comparatively smooth surface of steel. Nevertheless the evidence goes to show that *properly made steel* corrodes very little, if any, more than wrought iron, especially in boilers, pipe, and other articles which cannot be coated. (See page 418.)

The properties of wrought iron are the nearest to those of pure iron of any commercial material, notwithstanding its slag. This is because the slag is mechanically mingled with the metal and does not alter some of its chemical and physical characteristics. Therefore wrought iron is preferred for electrical conductivity purposes and as a metal with high magnetic power, for armatures of electromagnets, etc. When under strain greater than it can withstand wrought iron stretches more uniformly over its entire length than steel, although the elongation closer to the point of fracture may not be so great. Much wrought iron is made today by the *bundling* and rerolling of wrought iron scrap, as described on page 68. This makes a much inferior product, the bundles sometimes even containing steel rolled into the pile. The advantages I have mentioned, the conservatism of engineers,

and the capital previously invested in puddling furnaces are the chief factors in keeping alive the manufacture of wrought iron. It was freely predicted that the invention of the Bessemer and open-hearth processes would bring about the extinction of the puddling process, but these prophecies have never been fulfilled, although the importance of wrought iron has waned very greatly in fifty years.

Summary.—In order of expense and of quality the different steels are arranged as follows: (1) Crucible; (2) acid open-hearth, (3) basic open-hearth, and (4) Bessemer. The amounts of the different kinds made in America to-day are shown in Table XIX. Though I have not made a direct comparison between certain of the classes, e.g., acid open-hearth with Bessemer, their relations may be easily learned by collating the other comparisons given.

Distinguishing Between the Different Products

Low-carbon steel pipe, merchant bars, horseshoe blanks, etc., sometimes masquerade under the name of wrought-iron; high-carbon open-hearth and Bessemer-steel merchant bars, tool blanks, etc., sometimes masquerade as "crucible steel," or perhaps "cast steel," which is the trade name for crucible steel; other deceptions are not unknown; indeed, even malleable cast iron is sold oftentimes as "steel castings." It is therefore important for engineers to understand the essential differences between these materials, although care in the wording of contracts and specifications should be the important consideration and should precede watchfulness over the products. The definitions of iron and steel materials are in such a confused and unsettled condition that it does not do to rely upon them at all, especially where a lawsuit may be involved; and contracts in clear, simple language, free from legal and metallurgical phraseology, are the best safeguards. But even where it is entirely plain what material is called for, there is always a temptation to substitute steel for wrought iron, Bessemer for open-hearth, basic for acid, and Bessemer or open-hearth for crucible steel. In case one such substitution is suspected, there are means by which the material may be tested, aside from its strength and ductility, which may or may not be in the contract. The tests are somewhat delicate and usually require the judgment and experience of an expert—one who has standard samples of the different grades of material for comparison, because the details of manu-

facture vary from district to district, and still more so with the purposes for which the products are to be used.

Wrought iron may be distinguished from low-carbon steel by the fact that it contains slag.[1] Usually, there is more than 1 per cent. of slag in iron and less than 0.5 per cent. of slag (including metallic oxides) in steel. The slag may be determined either by chemical or microscopical analysis. Normal wrought iron is practically free from manganese, while normal Bessemer and open-hearth steel will contain 0.4 per cent. or more. Wrought iron generally contains more than 0.1 per cent. phosphorus, while good steel should never do so. Charcoal iron has less slag, less sulphur and less phosphorus than puddled iron.

Crucible steel normally has less than 0.4 per cent. manganese and more than 0.2 per cent. silicon, while open-hearth and Bessemer steels normally have more than 0.4 per cent. manganese and less than 0.2 per cent. silicon. In the case of steel castings, however, this rule for silicon does not apply, as Bessemer and open-hearth steel castings are sometimes as high as 0.6 per cent. in silicon. It is possible—but not usual—to make both Bessemer and open-hearth steels low in manganese. Be it noted that when crucible steel is ordered low in carbon, there is a much greater temptation to substitute another steel for it.

Acid open-hearth steel may be distinguished from basic open-hearth steel by its being normally higher in silicon, and usually in phosphorus also, but lower in manganese. The same differences exist between acid and basic Bessemer steel.

Basic open-hearth steel may be distinguished from Bessemer steel by its lower manganese, silicon, phosphorus and (generally) sulphur, as well as by the fact that it dissolves much more slowly in dilute hydrochloric and sulphuric acids.

It is possible to place such physical specifications in a contract as to practically insure obtaining the grade of material ordered. For example, such a high degree of ductility may be demanded, especially the percentage elongation in ten or twenty feet, that nothing but wrought iron will give it; the strength and ductility may be put so high as to make it too dangerous to try to supply anything but crucible steel for the order; or they may be put a little lower so as practically to preclude Bessemer steel. The average physical difference between acid and basic open-hearth steels is not great enough to make this method of assurance so

[1] The threading test for wrought iron and steel pipe is unreliable.

practicable, but it is possible in the case of basic and acid Bessemer steel in England, where alone both these kinds of steel are made in important quantities.

Prices of Steel, Etc.

We may at this point insert, for the sake of many persons interested in the commercial side of the iron and steel industry, some average prices of a few products, which will give an idea of the representative value of all.

AVERAGE PRICES
1910
Ore and Pig Iron per Long Ton; Others per 100 Pounds

Iron ore, Mesabi, non-Bessemer[1]	$4.00
Iron ore, Mesabi, Bessemer[2]	4.75
Iron ore, Old Range, non-Bessemer	4.20
Iron ore, Old Range, Bessemer	5.00
Pig iron, Bessemer	17.10
Pig iron, No. 2 Foundry	15.83
Pig iron, Southern Foundry, at Cincinnati	14.00
Pig iron, Basic	15.67
Ferro-silicon, per long ton, 50 per cent. silicon[7]	52.00
Ferro-manganese, per long ton, 80 per cent. manganese	42.48
Ferro-chrome, high carbon, per long ton, 60% Cr	100.00
Ferro-chrome, low carbon, per long ton, 60% Cr	450.00
Ferro-titanium, per 100 lb., 15% Ti	15.00
Ferro-vanadium, per lb. of vanadium contained[6]	4.00
Rails, Bessemer, per 100 lb	1.25
Rails, Bessemer, nickel steel, 3 1/2 per cent. nickel	2.37
Rails, open hearth (usually Duplex process)	1.34
Structural beams and plates	1.45
Structural shapes, nickel steel, 3 1/2 per cent. nickel	3.45
Wrought iron bars	1.43
Black sheets, No. 28 base	2.29
Wire nails	1.75
Cut nails	1.72
Crucible tool steel bars[4]	$4.50 to $17.00
Chrome steel, chrome-nickel steel	10.00 to 14.00
High-speed tool steels, etc[5]	15.00 to 90.00
Manganese steel castings[3]	11.00 to 25.00
Carbon steel castings	1.25 to 15.00

[1] Base 51.5 per cent. iron.
[2] Base 55 per cent. iron, under 0.045 per cent. phosphorus.
[3] The price of all castings largely depends on molding costs.
[4] Price depends on maker, brand, etc.
[5] Price depends on content of Tungsten, etc., and on whether heat-treated by maker or not.
[6] This is 1911 price; 1910, $5.00.
[7] This is manufactured in electric furnace; the blast furnace product containing 10 per cent. silicon, about $22.00.

VII

DEFECTS IN INGOTS AND OTHER CASTINGS

Besides the dangers already mentioned in connection with improper methods of manufacture, excessive amounts of impurities, etc., iron or steel may suffer from damage caused or developed during casting. The commonest defects which may appear at this time are: (1) Blow-holes, or gas bubbles enclosed in the body of the metal; (2) a pipe, or shrinkage cavity; (3) ingotism, or the formation of large-sized crystals; (4) segregation, or the concentration of impurities in localities; (5) checking or cracking of the casting because of strains produced when the metal is hot and tender. Avoiding these defects cannot make bad steel good, but their presence may make good steel bad, and therefore to guard against them is an important part of the processes.

Blow-holes.—Blow-holes are especially liable to occur in steel, particularly in low-carbon steel. When the metal is in a molten state, it readily dissolves certain gases, such as hydrogen, nitrogen, oxygen. Upon solidification these gases come out of their state of solution, but may become entangled in the steel and cause a gas bubble or cavity varying all the way in size from microscopic proportions up to an inch or more in length. The formation of these blow-holes is precisely similar to the formation of air bubbles in ice; water dissolves a good deal of air while in the liquid state and, as we all know, it is well-nigh impossible to freeze the water without obtaining a great many air bubbles in the ice, due to the separation of this air during freezing. The danger in the case of steel is not so great as in the case of ice, and it is by no means impossible to obtain steel absolutely free from this defect. Apparently, the reason for this difference is that the gas separates from steel a short time before solidification is complete, and thus the bubbles have some opportunity to escape before they are enclosed in the solid. Also, steel passes through a pasty stage during solidification, as we shall learn later, and therefore gives a better opportunity for the gas bubbles to pass away.

Another cause of blow-holes in steel is undoubtedly the presence of oxide of iron in the metal. This oxide of iron reacts with the carbon added in the recarburizer and forms carbon monoxide gas (CO), which may be produced during the entire solidification period and thus cause many blow-holes.

Prevention of Blow-holes.—That oxide of iron is one of the chief causes of blow-holes is shown by many things; for instance, (1) steel known to be highly oxidized is very liable to blow-holes; (2) cast iron, which from its chemical composition can never be much oxidized,[1] is never subject to blow-holes; and (3) the addition to steel of deoxidizers prevents the formation of blow-holes.

Chief among the deoxidizing elements which are added for this purpose are manganese, silicon, and aluminum. These elements seem to act partly by deoxidizing the iron and carbon, in both ways preventing the formation of carbon monoxide, and partly by increasing the solvent power of the solid metal for gases, so that a less amount separates. The amount of these deoxidizing substances necessary to be added will depend largely upon the extent to which we desire to prevent the formation of blow-holes. In the case of steel castings it is often necessary that blow-holes be entirely prevented, but in the case of ingots which are to be subsequently forged or rolled it is not necessary that blow-holes should be absent altogether, because they will be closed up under the pressure of the mechanical work and their sides welded together. Indeed, their presence is sometimes desired, because when they separate from the steel they occupy space, thereby counteracting to a certain extent the shrinkage of the metal during solidification and tending to reduce the volume of the shrinkage cavity or pipe. For this reason a small number in some harmless locality is often intentionally allowed to form in steel ingots. Mr. Brinell found in his steel-works that if the percentage of manganese plus 5.2 times the percentage of silicon is equal to 2.05 or more, the steel will be entirely free from blow-holes. In this case, however, the pipe will be large. If this sum is equal to 1.66, the steel will contain a harmless number of minute blow-holes, but the pipe will be small. This figure is therefore about the correct amount for ingots under conditions similar to those of Mr. Brinell's experiments, and not far different in any event. Mr. Brinell also found

[1] That cast iron is sometimes partially oxidized is claimed by several eminent authorities, and the evidence presented makes us hesitate to deny that a certain variety of wild cast iron owes its peculiar behavior to the presence of some partially oxidized constituent (perhaps the oxysulphide of iron, as suggested by J. E. Johnson).

that the addition to the steel of 0.0184 per cent. of aluminum will give approximately the same result as that given by the amount of manganese and silicon last mentioned, 1.66.

Location of Blow-holes.—The number and size of blow-holes is no more important, however, than the position they occupy in ingots in relation to the external surface. Even in castings, blow-holes, if present, should be deep-seated, as they are then less liable to be exposed by machine work performed on the surface. In the case of ingots the deep-seating is of still greater importance, because then the blow-holes may be closed up before they have an opportunity to break through to the surface and thus become oxidized on their interior. The normal gases in blow-holes are

FIG. 115.—SKIN BLOW-HOLES.

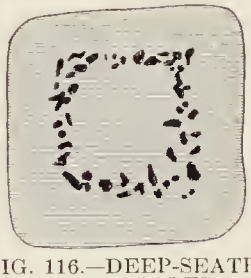


FIG. 116.—DEEP-SEATED BLOW-HOLES.

FIG. 117.

reducing in effect, and thus the interior surfaces of the holes are bright and silvery in appearance and readily weld together; but if they become oxidized they will never adhere firmly. For instance, a blow-hole near the surface, as in Figs. 115 and 117, is liable to break through to the exterior when the ingot is put under pressure. This not only causes a crack in the steel, but allows the air to oxidize the interior of the hole and thus prevent the crack being welded up by the rolling. It is not at all uncommon to see a number of these openings form during rolling when the blow-holes are near the surface.

As the percentage of manganese plus 5.2 times the percentage of silicon decreases from 1.66, the blow-holes become correspondingly deeper-seated. Finally when this sum becomes as low as 0.28, the blow-holes are harmlessly located in the interior. It is usually impracticable, however, to get the manganese and silicon as low as this in steel, because manganese is needed to counteract the bad effect of sulphur and oxygen.

The location of the blow-holes is also very largely dependent upon the fluidity of the metal when first cast into the molds. The more fluid it is, other things being equal, the nearer will the blow-

holes be to the surface of the solid ingot. On the other hand, if the casting temperature is too low there will be a dangerously large number of blow-holes in the steel (see Fig. 117), because it solidifies so quickly that very little opportunity is afforded for any part of the dissolved gases to escape. The fluidity of the steel depends partly upon its temperature and partly upon the amount of impurities in it. For instance, pig iron is fluid at a temperature at which steel is solid; high-carbon steel is fluid at a lower temperature than low-carbon steel. Therefore every different kind of steel has a different correct casting temperature; but we have already learned (p. 89) how to determine this by means of the skull left in the casting-ladle, and it is evident that this test applies equally well to all grades of steel. It is to be observed that low-carbon steel suffers greatly from blow-holes, because the more the carbon the less the liability to oxidation of the steel.

Pipes.—When steel is poured into a mold, it forms almost immediately a thin skin of frozen metal against the cold surface of

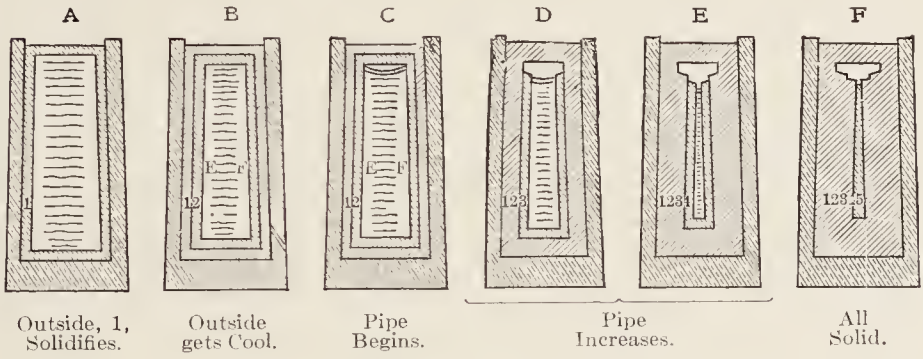


FIG. 118.—SOLIDIFICATION OF AN INGOT.

the sand or iron. The radiation of heat thereafter necessarily takes place through these surfaces, and therefore a casting will usually complete its solidification by the formation of thicker and thicker layers of solid metal around all the sides. The top, however, will usually remain molten longer than the rest because the hottest metal is usually at this point, having been the last to leave the ladle, and also because the heat is not conducted away by the air as fast as by the walls of the mold. This is especially true where the casting is poured into an iron mold—for example, in the case of ingots (see Fig. 118). But it is evident that at some period a stage will be reached when all the outside of the ingot, or casting, will be covered by a skin of solid metal while the interior

will still be liquid. The liquid interior will continue to freeze and will, at the same time, contract. The result will be the shrinking of the molten mass away from the solid walls and consequently the formation of a cavity, known as a "pipe," in the interior. This pipe will be filled with the gases evolved by the steel during solidification. Professor Howe has shown that the volume of the pipe is too large to be accounted for altogether by the shrinkage of the steel during solidification, and has shown that the rate of contraction of the inner walls of the ingot being greater than the rate of contraction of the outer walls, a virtual expansion of the outer walls is caused and a consequent enlargement of the pipe.[1]

The portion of the steel containing the pipe is of course defective and should be discarded at some time subsequent to casting. In the casting of ingots the upper part, which contains the pipe, is cut off during the rolling or forging and goes back to the furnace to be remelted as scrap. In the casting of steel castings there is a large adjunct to the castings situated above it, and so regulated in size and otherwise that it freezes after the casting itself, and thus always contains a supply of molten metal which runs down and fills any cavity that forms in the casting. This adjunct is cut off when the casting has cooled. In other words, the "riser" or "feeder," as this extra part is called, serves the same purpose for a steel casting as the upper part of an ingot does for the ingot.

Cast-iron castings do not form a pipe under ordinary circumstances, because cast iron expands during solidification on account of the separation of graphite, as we shall learn later. Under certain circumstances, however, there may be enough difference in expansion between the inside and outside of cast-iron castings to produce a porous spot which, while not exactly a pipe, is due to similar causes. We shall discuss this matter further in Chapter XII.

Lessening the Volume of the Pipe.—If the steel were poured into the mold so extremely slowly that it would solidify in layers from the bottom upward there would be no pipe. Therefore one method of lessening the volume of the pipe is by slow casting. We have already noted another method, namely, permitting a small number of blow-holes to form, which causes a certain amount of expansion to the steel during solidification and thus diminishes its shrinkage. Another way is to use wide ingots because this reduces the difference in contraction between the

[1] No. 71.

inner and outer layers of the ingot, which, as I have already stated, caused a virtual expansion of the outer walls and thus enlarged the cavity. Casting in sand molds has the same effect because radiation is not so rapid through sand as through metal. Still another method is to prevent the steel forming a solid skin over the top by constantly stirring and breaking it up with an iron rod. This method is often resorted to with the risers of steel castings, with very beneficial results.

Bottom Casting.—In the case of steel castings, and less frequently in the case of ingots, the metal is poured from the ladle into a runner which delivers it at the bottom of the casting (see Fig. 193, p. 226). With steel castings this is often necessary in order to prevent dirt getting into the casting. It also has a similar effect on ingots, because it prevents slag getting into the molds and also prevents metal from spattering up on the side of the mold and forming what is known as a "cold-shut," that is, a part of the metal which is not melted in with the rest. In both cases, however, this bottom casting has the effect of increasing the volume of the pipe and also of making the pipe extend deeper, because at the end of casting the hottest metal is at the bottom instead of at the top.

Casting with the Large End Up.—Risers on castings are almost always made with the top end larger than the bottom, in order that the pipe may be less in volume and shorter in depth. At steel-works, however, the ingot molds are always tapered slightly with the large end at the bottom, in order that the mold may be easily drawn off the top (see p. 90). This results in the large end of the ingot being down, and consequently in the pipe being larger in volume and very much greater in depth.[1] Because of this advantage Professor Howe has proposed certain mechanical arrangements by which the ingot may be cast with the large end upward.[2]

Liquid Compression of Ingots.—If the pipe is caused by the difference in expansion between the inside and the outside of an ingot, it is evident that putting sufficient pressure upon the outside when the walls are solid but the interior is still liquid will prevent the formation of a pipe. Numerous processes have been devised for effecting this liquid "compression," some of which are in operation at steel-works and produce ingots that are entirely

[1] No. 72.
[2] See No. 71.

free from pipes. In Whitworth's system the ingot is raised and compressed lengthwise against a solid ram situated above it, during and shortly after solidification.[1] In Harmet's method the ingot is forced upward during solidification into its tapered mold.[1] This causes a large radial pressure on its sides. In Lilienberg's method the ingots are stripped and then run on their cars between a solid and movable wall. The movable wall is then pressed against one side of the ingots.[2]

Ingotism.—When iron and steel freeze they crystallize, and these crystals grow with great rapidity, so that if the passage through the solidification period is slow they will attain a very

FIG. 119.—INGOTISM.

large size. This formation of large crystals is known as "ingotism." It is especially liable to occur if the metal is cast at too high a temperature or is allowed to cool through the solidification period at too slow a rate.[3] In the case of steel, ingotism may be detected by breaking the casting, when the large size of the crystal faces or facets may be observed.

Damage Due to Ingotism.—Large crystals always produce weakness and loss of ductility, for the large crystals do not adhere to one another as firmly as when there is a more intimate asso-

[1] See page 373 of No. 1.

[2] See No. 73.

[3] In the case of cast iron, large crystals formed during solidification produce what is known as an "open grain"; we shall consider this more particularly in Chapter XII. The name "ingotism" is not usually applied to this open grain in cast iron.

ciation; consequently steel that shows ingotism will be tender. In the case of steel castings, they will not give as good a result in the testing machine; in the case of ingots they will be liable to tear during rolling or under the hammer.

Remedy for Ingotism.—Ingots in which large crystals have formed during solidification may be brought to a high degree of strength and ductility by forging or rolling, because the mechanical work crushes the crystals and reduces them to a smaller size. The work must be done very carefully at first, however, or cracks

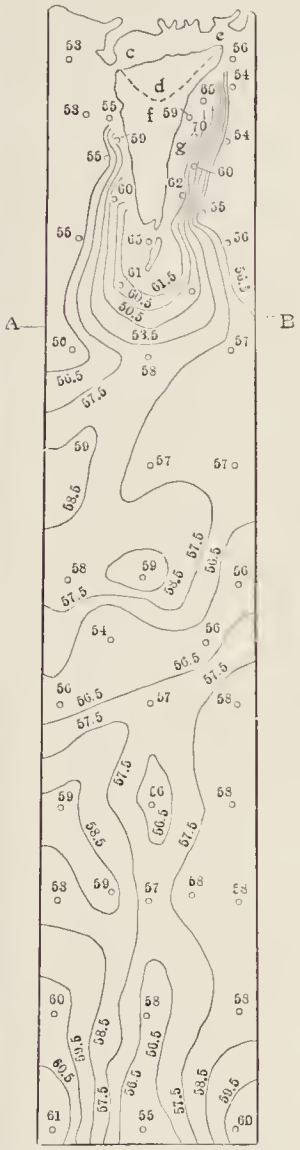


FIG. 120.—LINES OF EQUAL CARBON-PERCENTAGE IN A STEEL INGOT.

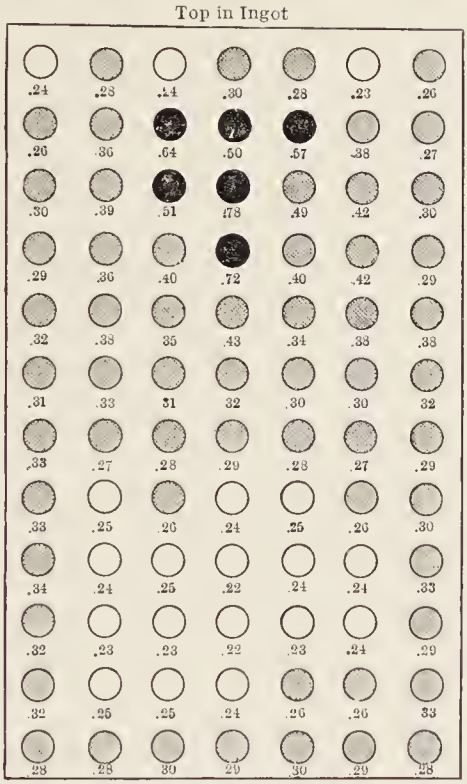


FIG. 121.—CARBON-PERCENTAGE AT DIFFERENT PARTS OF A STEEL INGOT.

will be formed that are not afterward welded up. Ingotism in steel castings is not so easy to cure; indeed, it is maintained by some authorities that its bad effects are never entirely obliterated. I am inclined to agree with this opinion, although annealing the

steel at a proper temperature (see Chapter XIV) will produce a very beneficial effect.

Segregation.—When either iron or steel is molten, the various impurities are dissolved in it, and some of them, especially carbon, phosphorus, and sulphur, make the metal more fusible, that is, they lower its melting-point. But the impurities are not as soluble in the solid metal, and therefore tend to separate on solidification; so it can readily be conceived how each layer that freezes, beginning at the outside, rejects some of its impurities to be dissolved by the still liquid mass in the interior. When the next layer freezes that too will tend to reject a part of its impurities into the contiguous molten layer, and thus the concentration will proceed so that as a general thing the portion of the metal richest in impurities, especially in carbon, phosphorus, and sulphur, will be that which freezes last. With ingots, this will evidently be at a point just below the bottom of the pipe, and it is found to be so in the great majority of cases; but the location of the richest segregate is very liable to vary, and rules can only be used for general guidance. For example, in Fig. 120,[1] the most impure metal is found at a point higher than the bottom of the pipe, and other unexpected exceptions occur. In the case of iron and steel castings, the most impure point will generally be near the top of the thickest section of metal. The riser is calculated to be the last portion to freeze and the richest segregate should be located in it.

In iron castings which contained on an average less than 1 per cent. phosphorus and 0.1 per cent. sulphur, I found on one occasion a segregate portion containing 1.856 per cent. phosphorus and 0.144 per cent. sulphur; and on another occasion I found one containing 2.43 per cent. phosphorus and 0.236 per cent. sulphur. An extreme case of segregation in steel is shown in the follow ng analysis:[2]

	Carbon Per cent.	Silicon Per cent.	Manganese Per cent.	Phosphorus Per cent.	Sulphur Per cent
Average	0.24	0.336	0.97	0.089	0.07
Segregate	1.27	0.41	1.08	0.753	0.418

[1] From page 205 of No. 71.
[2] From page 373 of No 1.

Treatment of Segregated Steel.—Segregation cannot be prevented, although, of course, it seldom takes place to the degree shown in the extreme cases that I have cited above. Nevertheless, there are always certain portions of the ingot or casting which are richer in impurities than others. An attempt is made to get this richer portion into the upper part of an ingot, or into the riser of a casting, and then it is cut off when the ingot is rolled, or when the riser of the casting is removed. It is therefore advantageous to cause the segregate to go as high up in the ingot or casting as possible. Whatever tends to raise the whole pipe higher up in the casting would, in general, tend to raise the segregate also; but wide ingots, or ingots cast in walls with low conducting power, though they tend to decrease the volume of the pipe, would not necessarily raise the segregate to a higher point. Furthermore, wide ingots will probably have a much greater degree of segregation than narrow ingots, other things being equal, because the wider the ingot the greater will be the number of layers of solidification, and consequently the greater concentration of impurities in the center.

Lessening Segregation.—Benjamin Talbot[1] has shown that quieting the steel by adding aluminum to it will lessen the segregation. J. E. Stead[2] argues that this result is due to the branches of crystals (commonly called 'fir-tree crystals'), which grow perpendicularly to the cooling surfaces when steel solidifies and mechanically entangle some of the impure metal, thus preventing it from traveling inward. Professor Howe calls this type of freezing the "land-locking type." When the steel is violently agitated by the escape of gas its rapid movement washes off the fir-tree crystals and prevents them from growing out into the liquid mass and entangling the impure metal. The quietness produced by aluminum, however, makes this growth possible.

Another important means of lessening the segregation is by making ingots narrow,[3] that is, by reducing the area of the horizontal cross-section; but this is often difficult of accomplishment. For example, if we cast fifty tons of open-hearth steel out of one ladle, it will take a very long time to cast all of this into small ingots, and therefore the first ingots cast will be too hot or else the

[1] Pages 204 to 223 of No. 74.

[2] Pages 224 to 228 of No. 74.

[3] Some metallurgists disagree with this and believe that the large ingots do not segregate so much. Nevertheless, I am inclined to think that the greater weight of evidence against them in this contention.

last ingots will be too cold. There is a difference of opinion as to whether or not rapid cooling decreases or increases the degree of segregation, and it seems probable that it acts in both directions, sometimes prevailing one way and sometimes in the opposite. On first thought it would seem that slow cooling must necessarily increase segregation, because it would allow more time for the impurities to separate from one layer of metal and dissolve in the next. On the other hand, slow cooling also favors the growth of the fir-tree crystals, and therefore opposes segregation. It does not seem possible, at the present time, to tell under what conditions we should have the one influence prevailing or the other.

It seems to be pretty well established that the greater the percentage of impurities present the greater will be the extent of the segregation. Therefore high-carbon steel should be cast with due care and narrow ingots used wherever possible. Generally when the phosphorus and sulphur are low (say, not more than 0.05 per cent. each), much segregation is not liable to occur, especially in low-carbon steels.

Occluded Oxidized Substances.—Steel and iron castings often contain after solidification particles of oxidized foreign substances. When large in size, these enclosures are commonly the result of accident, negligence or ignorance, and therefore could usually have been avoided by the exercise of due care, but, in microscopic particles, aggregating as much as 0.25 to 0.30 per cent. of the weight of the metal, they are often found in Bessemer and open-hearth steels, not as a result of chance, but as a regular occurrence. Oxides and sulphides of iron and manganese, oxide of silicon, and tiny particles of slag, are the commoner examples of these enclosures. Entangled particles of slag seem to be due to their having become caught in the solidifying metal before they had an opportunity to rise to the surface. No doubt the bulk of the oxides of manganese and silicon originate through the recarburizing reactions in the bath, and the tiny particles thereof are retained because they cannot separate immediately. Like the cream in milk, time must be allowed for them to rise to the surface. The same necessity is felt to an even greater degree in the case of sulphide of manganese, which separates from a molten bath of iron or steel only upon long standing. The sulphide of iron appears to be actually soluble in the molten metal and not to separate until after solidification.

All these occluded oxidized particles are harmful to the metal, to the same extent as microscopic blow-holes, for example. It is now commonly believed that many previously unexplained failures of steel are due in part at least, to such defects, and the "shelling" off of the surface of railroad rails and locomotive tires is often directly traceable to this cause.

Titanium.—Titanium is now often used in steel and cast iron baths for the purpose of a final deoxidation of the metal and its impurities, following the usual treatment for this object by means of manganese and silicon. Titanium has a strong chemical affinity for oxygen and will remove from the metal traces of oxygen which do not yield to the ordinary recarburizing reactions. It also has the further and apparently unique property of causing occluded oxidized substances to separate more readily, thus avoiding some of the harmful effects noted in the previous section. The most notable instance of titanium treatment is in the manufacture of railroad rails and during the year 1910 more than 5 per cent. of the total rail production of the United States was treated with this element. The beneficial effects of the titanium treatment, from the standpoint of the railroad rail user, are: (1) Increased life of rails—say from 200 to 400 per cent.; (2) less brittle (*i.e.*, tougher) rails under the drop test; (3) a stronger metal, and (4) less flaking off of the metal in the head. Some railroads find that the slightly higher cost of the titanium-treated metal justifies its use in rails in all parts of the line, and others employ it at present only on curves or at other points where the wear is unusually heavy.

The treatment consists of a physicing of the molten steel (either in the bessemer or open-hearth furnace, or in the ladle into which the product of the furnace is being poured after the end of the operation) by means of about 0.3 to 0.6 per cent. of an alloy containing 10 to 15 per cent. titanium, about 80 per cent. iron, 5 to 8 per cent. carbon, 0.35 to 1 per cent. silicon and all other impurities guaranteed to total less than 1/2 of 1 per cent. The titanium alloy must be added last, after the requisite amount of carbon, silicon and manganese. Aluminum must not be used for purifying the same steel in which the titanium alloy is employed and if the titanium alloy is not used subsequently to the carbon, manganese and silicon, its essential ingredient is liable to be excessively oxidized and wasted.

In the bessemer process the titanium should be shoveled into

the stream of metal which is being poured into the ladle, the steel having been previously recarburized in the converter. As the titanium alloy reacts energetically with the slag and may therefore be wasted, it is especially recommended that it have the maximum possible amount of churning and stirring with the metal before much slag enters the ladle. For this purpose it is well to let the stream enter a little off center of the ladle in order to give the molten bath a sort of gyratory stirring. After this treatment it is well to hold the metal about 3 min. in order that the titanium may complete its action and carry off as much as possible of the dissolved nitrogen, oxygen and entangled slag.

In the acid open-hearth process the same general procedure is followed, except that the metal should be held perhaps 5 or 10 min. to give the impurities released by the titanium time to pass off with the slag. Where, however, the titanium is added in the acid open-hearth furnace the greatest care must be exercised to keep it from contact with the slag and it must be rabbled into the metal as quickly and thoroughly as possible. The bath must then be gotten out of the furnace at the earliest possible moment as every delay tends to undo the purification work performed by the alloy. In basic open-hearth steel it is well to add at least three-quarters of the manganese in the bath; then add the remainder of the manganese and silicon at the earliest possible moment in the ladle and follow with the titanium alloy, using the precautions already mentioned for mixing and dissolving it thoroughly in the metal and keeping it out of contact with the slag.

Under no circumstances should the titanium alloy be preheated before it is added, or be used in conjunction with aluminum.[1] These warnings are more than precautions that should be observed; they are quite necessary to obtain success in the use of titanium, and should be regarded with at least as much respect as a good steel maker pays to any essential of correct practice.

Besides its use as a "super-purifier" for rail steel, titanium is being used for treating steel and iron rolls, whose resistance to abrasion and shock it is said to increase; for steel castings; for chain of high and low carbon, gears and pinions, tires, die plates and heads, propeller shafts, driving rods and other forgings,

[1] However, W. Venator testifies to the contrary, and states that he finds aluminum beneficial.—*Stahl and Eisen*, Vol. XXX, pp. 650–4—but he used titanium metal instead of the 10 per cent. ferro-alloy.

automobile steels, tool steels, cast iron ingot molds, acid pots and chilled car wheels. It is said to improve the qualities of other alloy steels such as nickel steels, chrome steels, etc.

Titanium is also said to remove nitrogen from iron and steel, titanium being one of the very few elements which attacks this comparatively inert gas. It is also said to lessen the segregation of steel ingots, which may be believed because of the well-known influence in this respect of agents which deoxidize and quiet the metal.[1]

Instead of introducing titanium by means of the so-called ferro-titanium alloy, it may be reduced by the Goldschmidt thermit process, although this is not as common practice. In this process we use powders consisting of oxide of titanium mixed with pulverized aluminum. When a reaction is started by heating the mixture, either with the heat in the molten bath, or by means of certain fuses, a reaction is produced whereby titanium is reduced, and at the same time, heat is generated.

$3TiO_2 + 4Al = 3Ti + 2Al_2O_3$ (evolves 65,200 cals. estimated).

Vanadium in Steel.—While titanium is used for the purpose of treating and superrefining steel and cast iron, it is not ordinarily employed to manufacture one of the socalled alloy steels in accordance with the definition on page 389. Vanadium, on the other hand, is used,—although generally, in conjunction with some other element, such as chromium or nickel,—to produce an alloy steel, but it is also used, like titanium, for the purpose of carrying the deoxidation beyond the point obtainable by means of manganese, silicon and aluminum. Vanadium has a strong chemical affinity for oxygen, and when added to the liquid iron or steel, to the extent of 0.15 to 0.30 per cent., after the usual recarburizing, it seems to cause further deoxidation of the metal and its impurities. Vanadium is usually added by introducing into the liquid bath small pieces of vanadium alloy, containing iron with varying amounts of vanadium, of which the 35 per cent. alloy is a common example. It is melted without difficulty by the heat of the molten bath and the vanadium dissolves in the metal, attacking the oxides present.

[1] George B. Waterhouse, *Proceedings, American Society for Testing Materials*, Vol. X, 1910, pp. 201–211.

VIII

THE MECHANICAL TREATMENT OF STEEL

Metals may be shaped either by pouring them while molten into a mold, as described in the following chapter, or by mechanical pressure. The choice of the casting or the mechanical method of shaping will depend on the cost of production, the size and form of the finished product and the purpose for which it is intended. Some shapes must be produced by casting, because they are either too intricate or too large to be shaped by pressure; others must be produced by pressure, because the service in which they are to be used demands the higher strength and ductility which mechanical work produces. Between these two classes, however, is a large number of forms, each of which is a study by itself. Financial considerations will govern in some cases, and the importance of quality in others. The advantage of quality is usually with the pressed material. Cost is in favor of castings except where many pieces are to be produced alike in shape and size.

Effect of Work.—Mechanical work will multiply the strength of steel from two to five times. In order to accomplish as much as this latter, however, it is necessary (1) to reduce the material to very small sizes, in order that the beneficial effect of the kneading action may extend throughout the mass, and (2) to finish the work cold, in order that the metal may have no opportunity to recrystallize. The ductility also will be increased at first by working, but again decreases if the metal is worked cold. The increase in strength and ductility is due (1) to decreasing the size of the crystals and closing the grain of the steel; (2) to the closing up of blow-holes, both large and small, which are almost all welded together under pressure at high temperatures, unless they are near enough to the surface to become oxidized inside, and (3) to increasing the cohesion and adhesion of the crystals. All these effects increase the specific gravity and hardness of the metal, and are more effective in these respects, as well as in increasing strength, if hot work is followed by cold work.

Crystallization of Steel.—Metals are crystalline substances, the individual components arranging themselves in regular forms unless opposed by the rigidity of the mass in which they form. Indeed, the metallic crystals grow with astonishing rapidity when the metal crystallizes from the molten state (i.e., solidifies), or even when it is in a mobile condition (i.e., at temperatures near or above a red heat). Once crystals have formed they cannot be reduced in size except by annealing (see Chapter XIV), or by breaking them up by mechanical crushing. These facts are important, because large crystals do not adhere to each other firmly, and thus they cause a weak and brittle mass. Iron and steel follow the same laws as other metals in these respects.

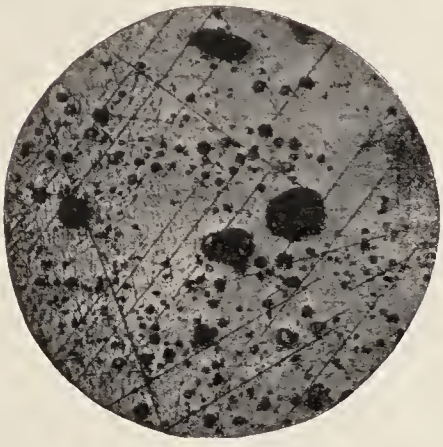


FIG. 125.—STRAIGHT SLIP BANDS IN WROUGHT IRON MAGNIFIED 60 DIAMETERS.
Unetched. (William Campbell.)

FIG. 126.—CURVED SLIP BANDS IN WROUGHT IRON MAGNIFIED 60 DIAMETERS.
Unetched. (William Campbell.)

Effect of Strain.—When a metal is strained, the crystals first stretch, and the amount of this stretching is directly proportional to the strain; when the strain is relieved, the crystals and the mass as a whole, return to the original dimensions. If the strain is greater than the "elastic limit," however, the crystals yield, and the particles composing them slip along the cleavage planes, so that a permanent deformation or extension occurs in the direction of the strain. This "elongation" is accompanied by a "reduction in cross-sectional area," and gives warming that the material is suffering from excessive strain. The extent to which these two forms of distortion precede rupture is usually taken as the measure of the "ductility" of the metal.

Rationale of the Effect of Work.—Mechanical pressure upon a metal crushes the crystals, mixes them intimately together, and breaks up the cleavage planes along which they would yield. If the work is finished above a red heat where the mass is still mobile, the crystals reform to a certain extent, decreasing the strength. The elastic limit of a structural steel rolled in this way will be a little more than one-half its ultimate strength. If the work continues while the metal is cold, there is no opportunity for the reformation of the crystals, and the strength, hardness, and brittleness are much increased.

Methods of Applying Pressure.—Aside from the differences of hot and cold working, the mechanical pressure may be exerted in one of three ways: (1) Instantaneously, by a blow, in which method the pressure is relieved before the metal has fully yielded to it; (2) more slowly, by rolling or wire-drawing, in which the pressure is relieved almost as soon as the metal has yielded to it; and (3) slowest, by presses, in which the pressure remains for a second or so after the metal has yielded. See page 214 to compare.

The Forging of Metals

The instantaneous application of pressure is man's first method of shaping metals and is accomplished by a blow from a falling weight, frequently aided by some other force. Examples of the first practice are found at the present time in the helve-hammer used at many small forges and steel-works. After the introduction of steam, however, this was used to raise the weight, and very soon steam-power was employed not only to raise the weight but also to force it downward for the blow, whose momentum was thus greatly increased. Hammers of this type, which is now the most prevalent, have been built capable of delivering a blow estimated as equivalent to 150 tons weight. Such large sizes are not now approved of, however, because of the inordinate expense for foundations, which must be deep and powerful in order to take up the force of the blow, while the constant jarring disturbs the foundations and alinement of machinery, even at distant parts of the plant. For very heavy forging work, such as armor-plate, etc., the hydraulic press is therefore preferred, and hammers are not often built in sizes above 30 or 50 tons.

Effect of Hammering.—A blow creates in a metal practically

nothing but compressive strains, which act chiefly in the vertical direction, and, by transmission, in the two horizontal directions. Because the pressure is relieved almost as soon as felt, the elasticity of the metal causes it to recover somewhat from the effect. This makes the effect of hammering superficial. Also the amount of yield to it is not great in proportion to its force, and therefore it takes more pressure to accomplish a result than

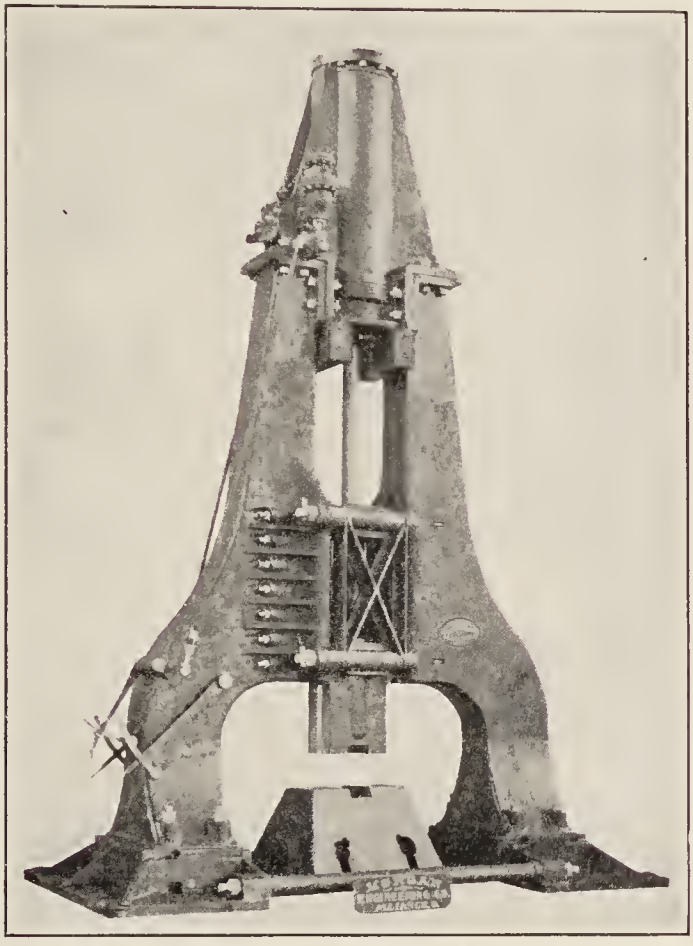


FIG. 127.—STEAM HAMMER.

would be the case if the application was slower. This makes hammering a slow process of reduction, but results in a better and more uniform working of the crystals on the surface at least, which is one of the chief reasons for the superiority of hammered over rolled material. Another and, perhaps, even more potent reason is the exact control of the operation which can be exercised by the expert forger, and more especially his control over the

temperature at which the work is finished, and over the varying force of pressure applied at different stages and temperatures. On the other hand, the effect of forging extends only skin-deep from the upper and lower surfaces.

Finishing Temperatures for Forging.—Forging seldom continues after the red heat is lost, but the exact temperature will depend upon the article and the properties which it is desired to have. The colder it is finished the closer to the exact size required it can be made, because it has less shrinkage to undergo; but it will also be harder, less ductile and stronger. The relation between the finishing temperature of mechanical work and the critical points of steel will be discussed in Chapter XIV.

Drop-forging.—There is a large variety of articles, such as parts of machinery, hammer-heads and similar tools, which are formed by the process known as "drop-forging." In this operation a piece of metal of the desired size is forged by repeated blows between a lower die, upon which it rests, and an upper die attached to the head of the hammer. These two dies are made in the desired form of the finished article, and the metal is squeezed into them until it has assumed the proper shape. Sometimes several pairs of dies are necessary to complete the finished shape (see Fig. 128). Drop-forgings are directly comparable with steel castings, to which they are superior in quality on account of the beneficial effect of the working. To be economically made, they must be ordered in large quantities, so that it will pay to make the costly dies of hardened steel—often an alloy. Even then, castings are sometimes cheaper, though forgings are still preferred on account of their quality. There are cases, however, in which drop-forgings may be made more cheaply, either because the shape is one that lends itself to rapid production in this way, or because it is one liable to cheeking, or requiring a large riser, if cast.

Forging Bars.—Crucible-steel ingots are often forged instead of rolled, because the material will bring a price high enough to pay for the superior method of working it. The ingot, after the top third has been broken off to remove the pipe and segregate, is heated to a bright-red heat, out of contact with the flame and fuel, and then tilted down under a hammer of about 10 to 15 tons size until it is about one-half as large on the sides and four times as long. One end is then reheated and drawn down to a bar of the desired size, under the same hammer, or under one of

less weight, and the long bar is then used as a handle while the other end undergoes heating and reduction. The finished size is produced by light taps of the hammer just before the blue heat appears, and often a piece of cold steel is laid beside it on the anvil

FIG. 128.—SOME AUTOMOBILE DROP-FORGINGS.

to more correctly arrest the downward blow. The finished bar will be so straight and true as to lead one to believe that it was produced by drawing through a die, or rolling in grooved rolls.

Forging Razors.—Flat bars for razor stock, made of cemented

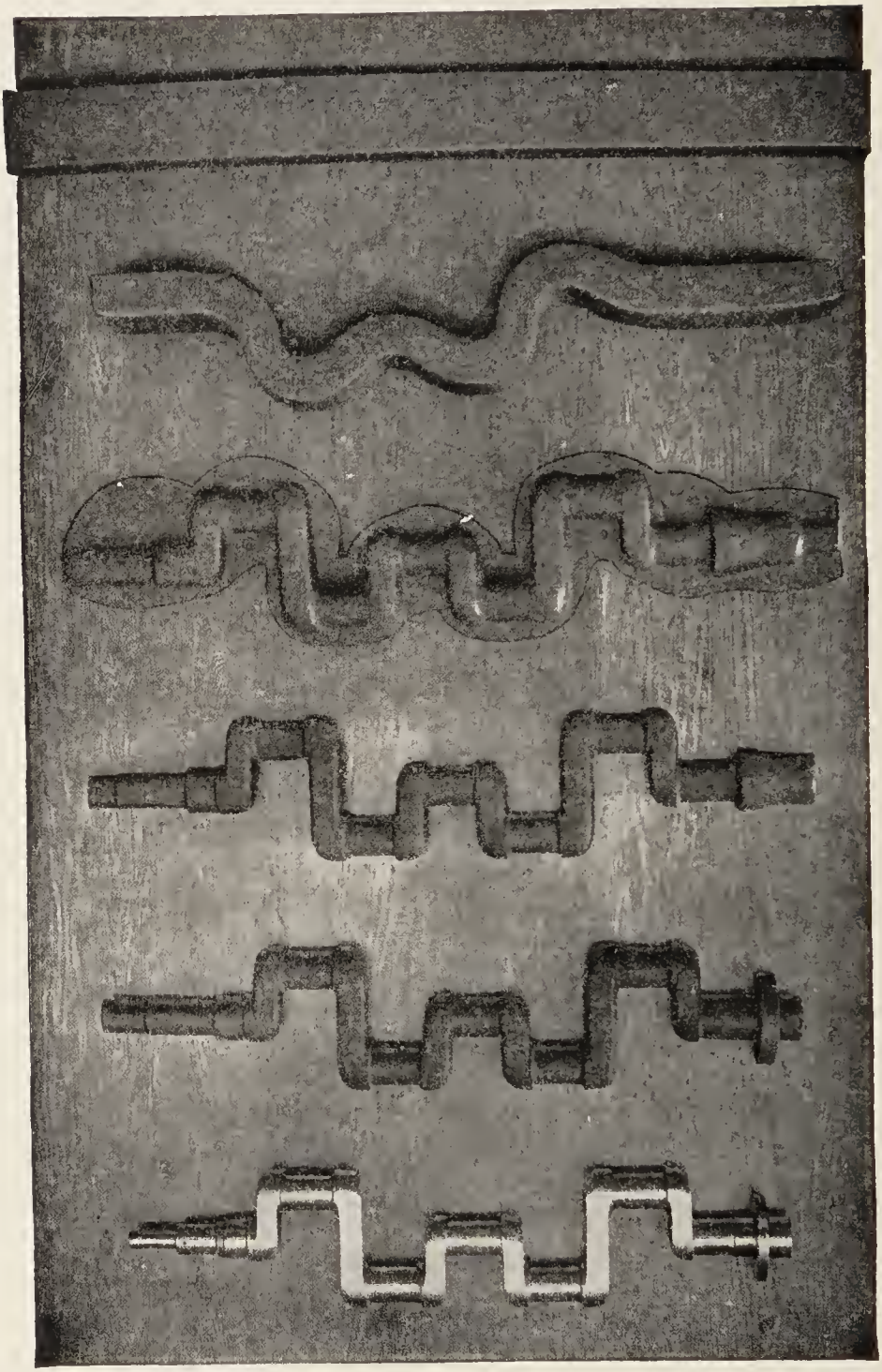


FIG. 129.—SOME STAGES IN THE MAKING OF A DROP-FORGING.

steel melted in crucibles without additional carbon, are produced in a manner similar to that outlined above, and then forged down by hand to the rough size of a razor. They are then stamped with the appropriate name and mark, drilled with a hole, heated to the correct temperature and hardened in water, after which the temper is drawn to the light or medium straw color (see page 383). The exact shape is then produced by grinding, care being taken not to heat the razor during this operation, lest it be tempered thereby, and the blade polished and fitted with a handle.

Forging Cannon.—Large cannon tubes are made from open-hearth steel ingots weighing perhaps 65 tons or so, more than one-half of which is discarded or "scrapped" during the process. In France and Germany, cannon-tube ingots have been made of crucible steel by pouring many crucibles into one mold, but the expense and the liability to heterogeneity because of the many small units is belived to outweigh the advantages due to the quality of crucible steel. The heating of the ingots must be done with great care, lest a crack or hollow be formed by too rapid expansion or by the expansion of the outside away from the interior, and for the same reason ingots of the form shown in Fig. 130 are usually employed, and those cast in sand molds are preferred because they are not liable to contain surface cracks produced by tearing the steel when the iron mold is withdrawn. Moreover, as reducing a flame as possible must be maintained, lest the carbon be oxidized in the outer layers of steel during the many hours required to attain the bright-red heat necessary.

FIG. 130.

During the long forging process reheatings of about an hour or so are necessary at intervals. Not more than the lower two-thirds of the original ingot is allowed to be present in the tube at the finish of the forging operation in order that the segregated and piped portion may be avoided. The blows are delivered on all sides of the ingot in order that the center of the tube shall be the same as the center of the original ingot, for this center portion is to be drilled out in the subsequent operations, and, as we have already seen, the center of the ingot is of looser texture and contains more of the segregate.

After the inner tube is forged, an outer tube is produced in a similar manner, but of larger size, so that it may be bored out to

fit over the carefully turned inner tube. After the boring the outer tube is too small to pass over the inner one, and it is therefore heated to a temperature of about 280° C. (550° F.) in a tall vertical furnace, which expands it so that it may be passed over the inner tube and "shrunk" upon it, greatly increasing its compactness and reinforcing it against the tremendous strains it is subjected to in service. Cannons are now frequently forged under presses instead of under hammers.

The Reduction of Metals in Rolls

If two rolls rotating as shown in section in Fig. 131 be made to grip a piece of metal, *A*, they will drag it between them and force it out on the other side reduced in thickness. The metal between the points *O O* and *NN* is being compressed vertically, while its

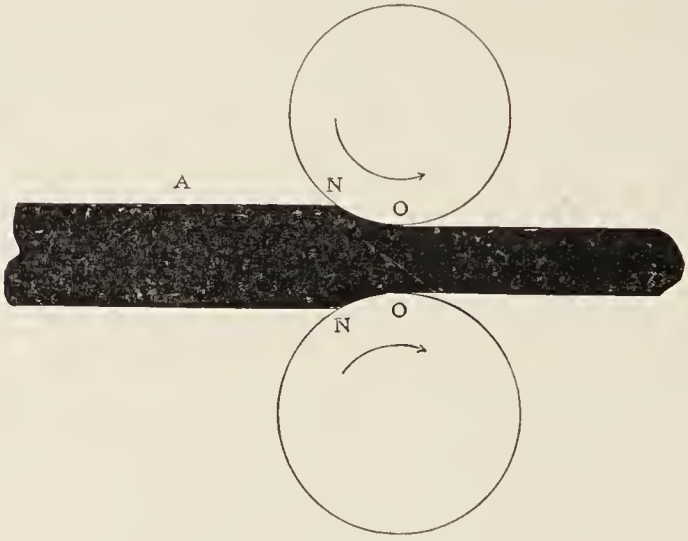


FIG. 131.

outer layers are suffering tension. In the case of a deep section, the unequal strain produced by unequal speed of travel is liable to tear the steel (see Fig. 165). The mechanical pressure is therefore not as uniform as in hammering, and acts for a longer period of time. Reduction can only take place vertically, as in forging, there being always a certain amount of expansion sidewise, and a large amount of extension in length. The metal at the points *N N* being forced backward, and that at the points *O O* being forced forward, the ends of the rolled section assume a shape somewhat like that shown in Figs. 132 and 133. The reduction

in area at each "pass" will vary between 5 and 50 per cent. of the original, and the work is very rapid. For example, a railroad rail may be produced, from an ingot having a section 18 in. square, in 22 passes, varying in amount of vertical squeeze from 8 to 50 per cent., only about five minutes being required for the whole operation, the piece traveling through some of the passes at a rate of ten miles per hour, and in some mills not being reheated after the ingot comes to the first pair of rolls. Some American rolling-mills produce over a mile of single rail per hour for 24 hours a day and 26 days per month. The temperature

FIG. 132.—SHAPE OF ENDS OF ROLLED METAL WHEN THE INSIDE IS THE HOTTER.

FIG. 133.—SHAPE OF ENDS OF ROLLED METAL WHEN THE OUTSIDE IS THE HOTTER.

at which the rolled material is finished is gaged with much less accuracy than in forging operations, and is always too high for the best quality of the steel, because economy of power urges the manufacturer to work the metal hot.

Pull-over Mill.—In a single pair or rolls, such as shown in Fig. 131, the metal, after passing between them once, must be handed or pulled over the top of the mill, to be fed in for a second pass. This type of train is known as a "pull-over" or "pass-over" mill. It can be used only for shapes small in size and that can be handled readily, and the action is slower than in a continuous operation, such as in a "three-high mill." The pull-over mill is simple and cheap to construct and operate, and is used especially for the rolling of plates and shapes from crucible steel, whose high price renders it less important to seek rapid output. It is also used very largely for the rolling of steel to be used for tin-plate. The upper roll is adjustable, so that any thickness may be produced.

Multiple-ply Plate, etc.—Three-ply plates for plow-shares, and five-ply plates or bars for burglar-proof safes and jail bars, are often made in this type of mill. We first roll independently thin plates of high-carbon, crucible, chrome steel

(or an equivalent alloy steel capable of becoming very hard upon quenching in water from a red heat), and thicker plates of wrought iron. For a plowshare, a plate of wrought iron will then be sandwiched between two plates of chrome steel, tied into a bundle with wire, and raised to a welding heat. The wire burns off in the furnace, but the bundle is grasped with a pair of tongs and fed into a pair of plain rolls, where it is welded into a plate of three-ply steel which is reduced to a thickness of a little over a quarter of an inch. This plate is trimmed and then hardened and used

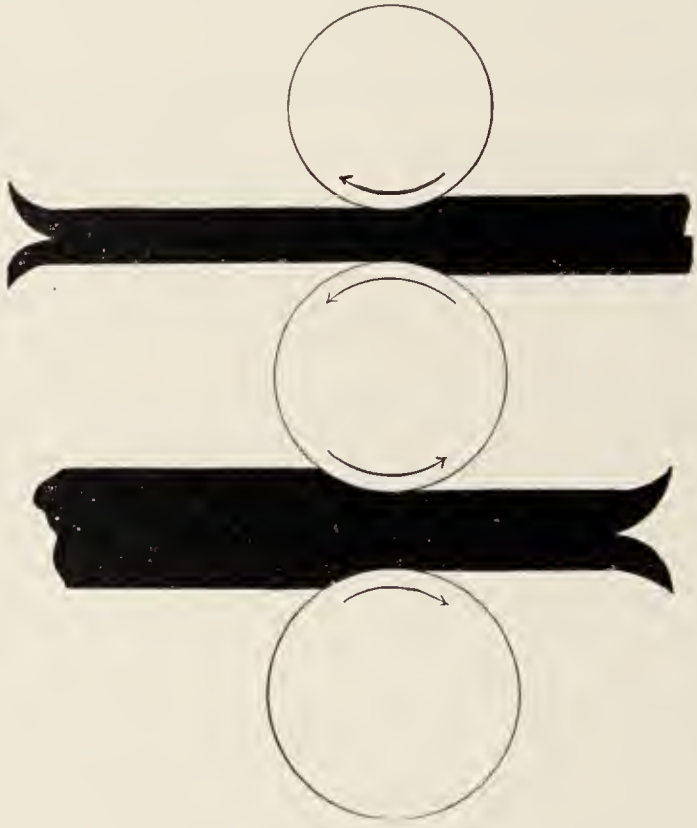


FIG. 134.

for a plow, the hard outer layers resisting the attrition and wear of service, and the ductile core resisting the shocks. For safes and jail bars we have an inner layer of wrought iron, then two layers of chrome steel, and then two layers of wrought iron, welded together and then hardened. A prisoner can neither file this, on account of the hardened chrome steel, nor break it with a sledge, on account of the soft iron, which is not hardened by quenching.

Three-high Mills.—When a piece is passed over a two-high mill, it is often rested upon the top of the upper roll, whose travel assist somewhat in the transfer. While watching this operation at the Cambria Iron Company's mill in 1857, John Fritz conceived the idea of the three-high mill, which is shown in section in Fig. 134. It will be seen that the piece receives work in both directions. At the present time the great bulk of the tonnage of steel and wrought iron produced, consisting of structural shapes, railroad rails, plates, wire rods, billets and bars, is finished in this type of mill. The output is large, because the rolls can be run very fast indeed (rod mills running 600 to 1200 revolutions per minute and sometimes passing the rod through at the rate of half a mile a minute in American practice[1]), and

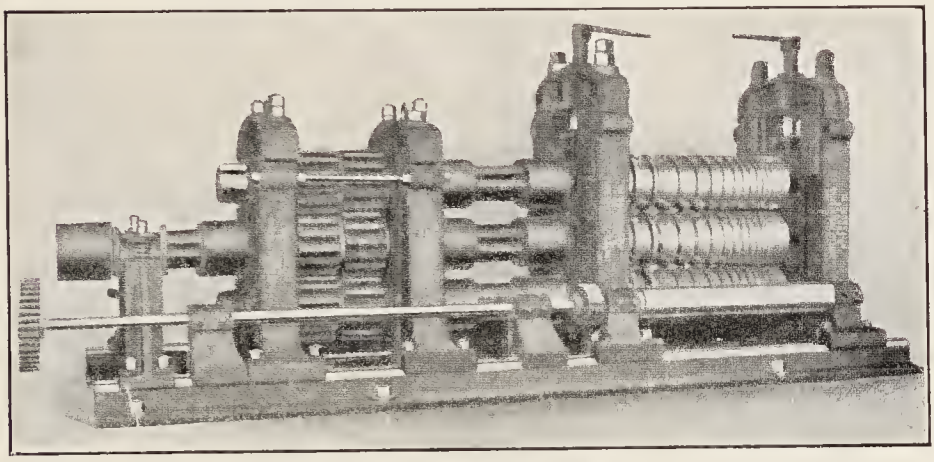


FIG. 135.—THREE-HIGH MILL.

two or more pieces may be passing through at the same time. The disadvantage of the three-high mill is the power necessary to raise large weights up to pass over the middle roll. Most Bessemer ingots are cast two tons or more in weight, and most open-hearth ingots from three tons to ten or more tons.

Reversing Mills.—Therefore ingots are often "cogged" in two-high reversing mills to avoid this consumption of power. Moreover, the two-high mills, which have an adjustable upper roll, have the advantage of being able to work an ingot gently at first, in case it shows a tendency to be "tender," that is, to crack in

[1] The reason for this rapid rolling is not only large product, but that the thin rods may not radiate their heat during the operation and thus be finished too cold. This rapid work actually raises the heat of the metal faster than it can be radiated, and rods are hotter at the end than at the beginning of the rolling.

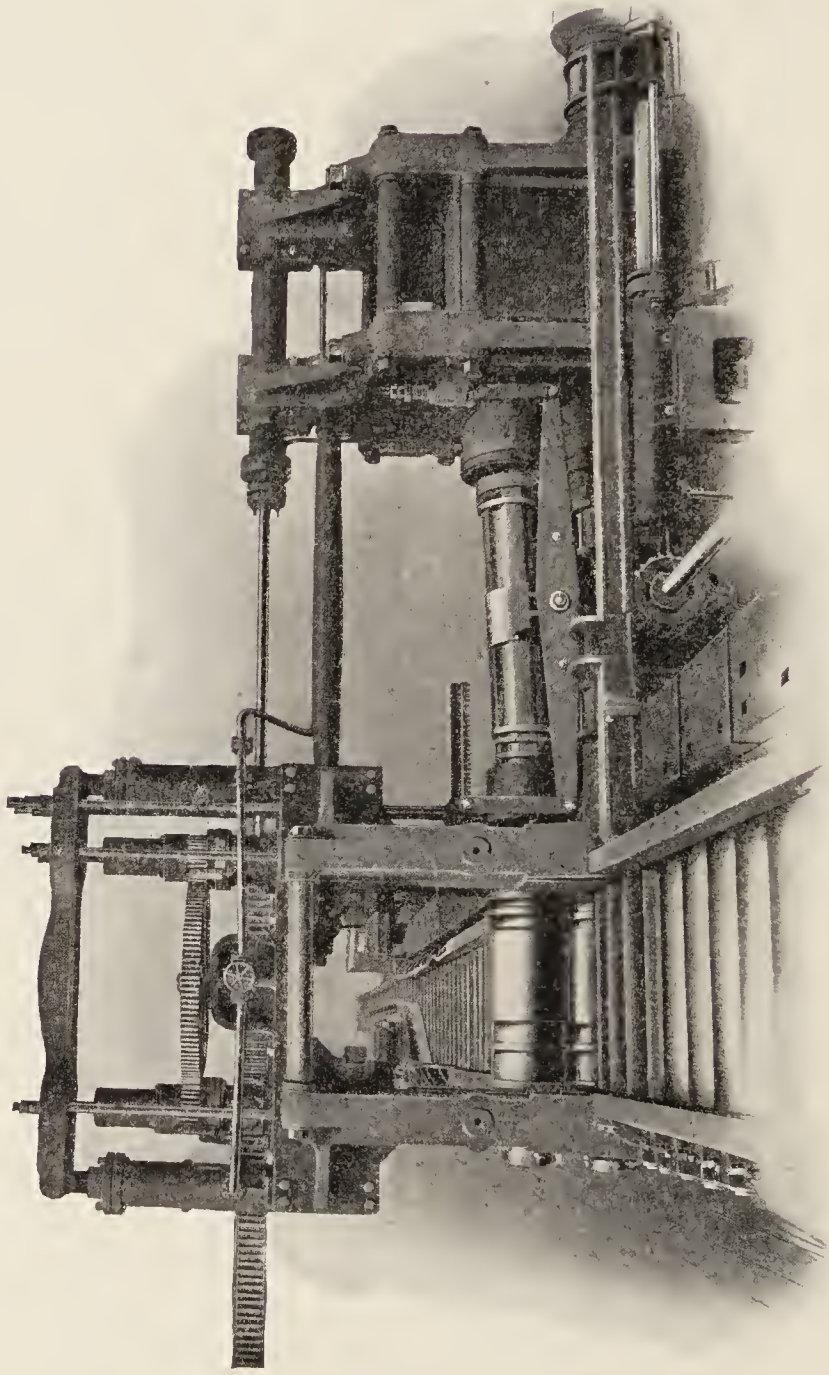


FIG. 136.—TWO-HIGH, REVERSING COGGING MILL

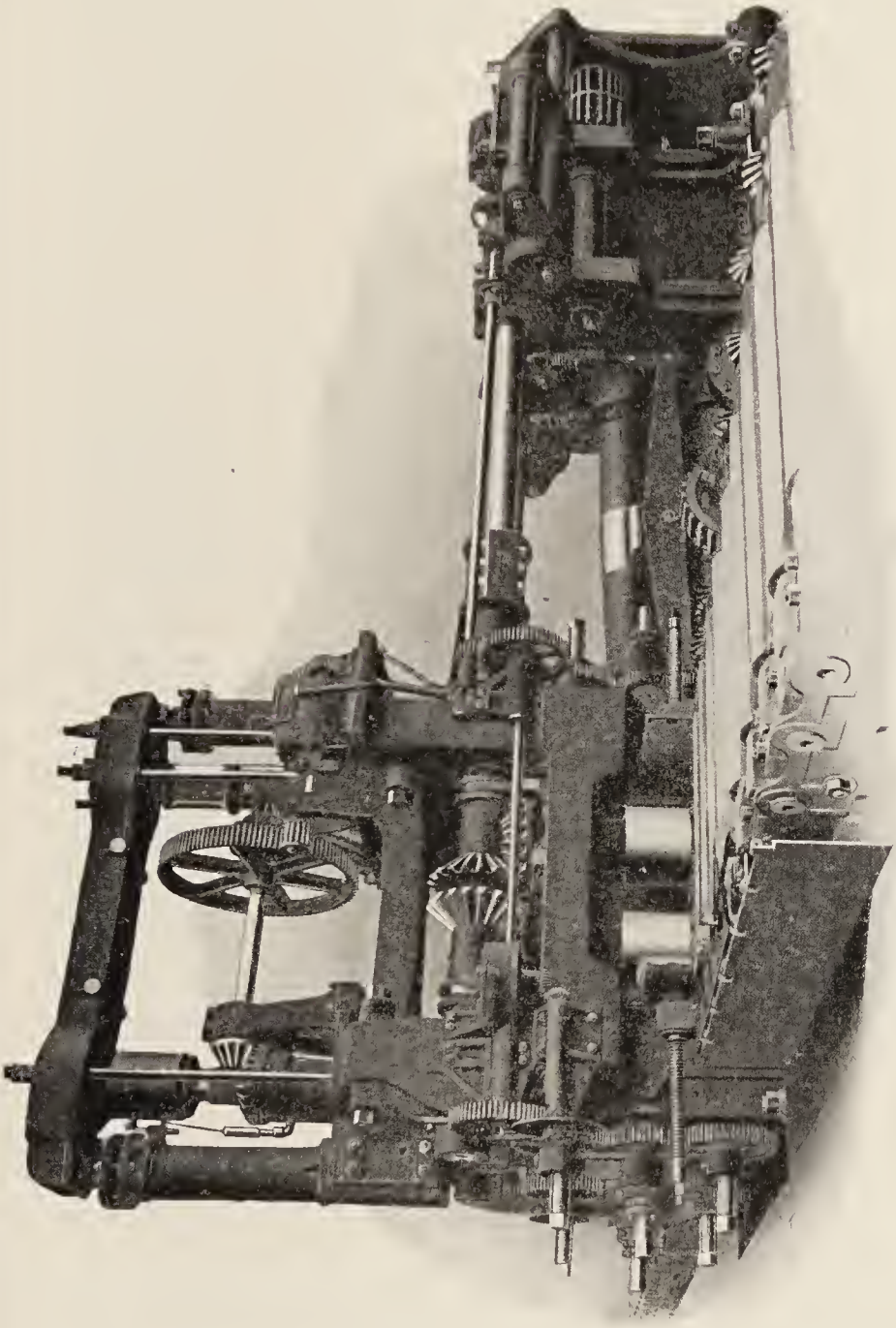


FIG. 137.—UNIVERSAL MILL.

spots when the pressure is applied. The disadvantages of the two-high reversing mill are its slowness and the severe strain on the engines, which are often reversed while running full speed.

Universal Mill.—During the rolling of metal there is a certain amount of expansion sidewise, which gives the piece a cross-section somewhat bulging on the sides, and makes the edges uneven, unless the rolls have collars which form a groove through which the metal passes. In 1855 R. M. Daelen, at Hoerde, Germany, devised a mill in which even edges could be produced at any width by having an auxiliary pair of vertical rolls, between which the piece passes immediately after it emerges from the horizontal rolls. These vertical rolls are adjustable to any width up to the capacity of the mill, and give only enough pressure to keep the edges even without producing any reduction. They are usually made to rotate with a surface velocity greater than that of the horizontal rolls, so as to prevent the serious buckling that would take place if the conditions were reversed. As this tension is not good for the edges of the metal and wears out the vertical rolls, some mills have independent control of drive for each pair of rolls, and others have friction-clutches connected with the vertical rolls, which allow them to run faster if pushed by the metal, but ordinarily run them at a slower speed. Universal mills are made two-high or three-high, and with vertical rolls on one or on both sides of the horizontal rolls. In England, the Universal mill is not as much in favor as grooved rolls because rolling-mill managers believe that the faster work of the latter more than makes up for the necessity for changing rolls whenever a new width is to be produced.

Parts of Rolling Mills

Rolls.—Rolls may be plain cylinders, by which plates and rectagonal shapes are produced, or they may be cylinders with "collars" at intervals, as shown in Fig. 138, in which large rectagonals with even edges may be produced; and the collars may be on both rolls, giving an "open pass," or may be on only one roll and extend into grooves on the other roll, as shown in Fig. 139, giving a "closed pass." With open passes, the collars cannot be made to quite touch, hence the name; and the pressure may squeeze some metal between them, forming a "fin" along the side of the piece. This results from "overfilling the pass."

The closed pass makes the upper roll weaker, and there is also a liability of the metal becoming wedged tightly between the collars and thus drawn all the way around the roll, with the result that something will be broken. Wedge-shaped grooves may be cut in the rolls, producing the "diamond" pass, in which small squares are made (see Fig. 139); or oval grooves make nearly round bars which are finished round in the last pass with almost no draft. Other forms of passes are shown in Figs. 135 and 141. In case rolls are weakened by deep cutting, as shown

FIG. 138.—CC=COLLARS. W=WOBBLERS.

in Fig. 139, they may be strengthened by stiffeners, *D*, while long rolls for producing wide plates are sometimes stiffened by an idle roll running on top, lest the springing of the roll make the plate thicker in the middle than at the edges.

Cast-iron versus Steel Rolls.—Cast-iron rolls are chilled upon the outside so as to produce a surface layer of white iron (see Fig. 282), which, after turning in a lathe, makes a very smooth surface for rolling and is especially advantageous for finishing-mills. They are not so good for the mills which do preparatory work, however, because they are not so strong, and because in pre-

paratory work we want a rough surface to assist in gripping the metal and drawing it through. Furthermore, they cost more to turn to the desired shape, and they cannot be turned down many times (see page 336), lest we get below the "chill." The greater cheapness of cast iron over steel, however, counteracts these factors of higher cost. Where the rolls must be very strong and yet not too large in diameter, and for sharp corners, which would crumble if made of cast iron, steel rolls are often used. The steel employed should be high in carbon—say 0.50 to 0.75 per cent.; but any case-hardening of steel is useless here, because the

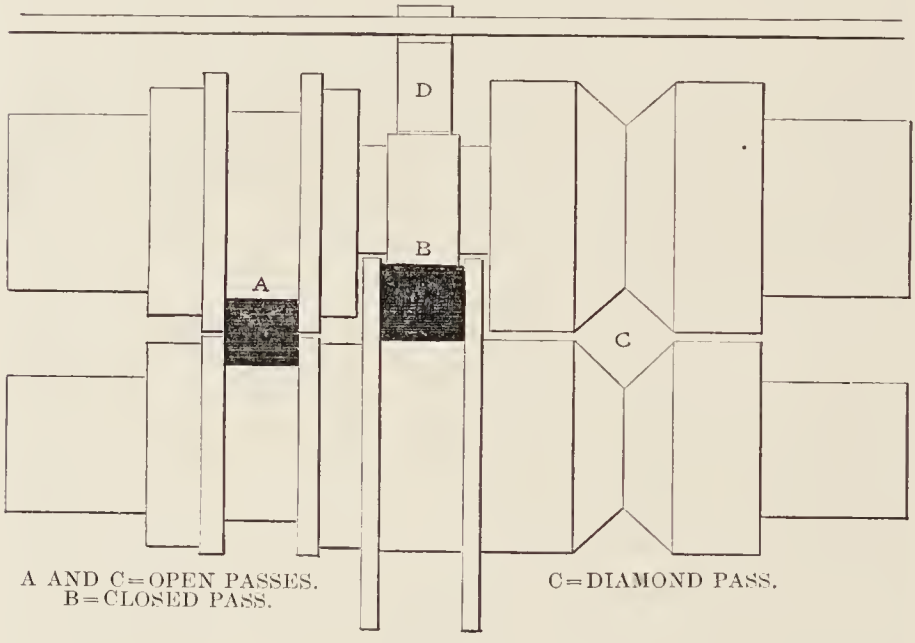


FIG. 139.

heating of the roll by the material passing through will soon draw their temper. This heating cannot be prevented altogether, though it is customary to have a stream of water flowing over the rolls. Sometimes nickel-steel rolls are used for strength. An analysis of roll metal of a very large American company is: 0.40 to 0.50 per cent. carbon, 0.65 per cent. manganese, 3.25 per cent. nickel, and 0.15 to 0.20 per cent. silicon.

Diameter of Rolls.—With smaller rolls, the amount of power consumed is less because the area of metal under vertical pressure is less. There is a limit below which the diameter cannot go, however, either because the rolls will not be strong enough to give the desired pressure, or they will not grip the bar. In

order to be gripped the upper and lower edge of a piece must touch the rolls at a point not more than 30° from the center line of the two rolls (see Fig. 140). Every effort is made to use smaller rolls, because the size of all the mills is regulated by them. The surfaces of all but the finishing-mill are usually "ragged" (i.e., made, rough, Fig. 141), to make the rolls give a better grip. Those to receive the ingots are ragged the most, with deep indentations somewhat like the cogs of cog-wheels, whence the name of "cogging rolls" for this mill.[1] The next trains, known as the "roughing rolls," are also deeply marked, but even then the piece must come within the 30° line, or time is lost in trying to make them bite the piece.

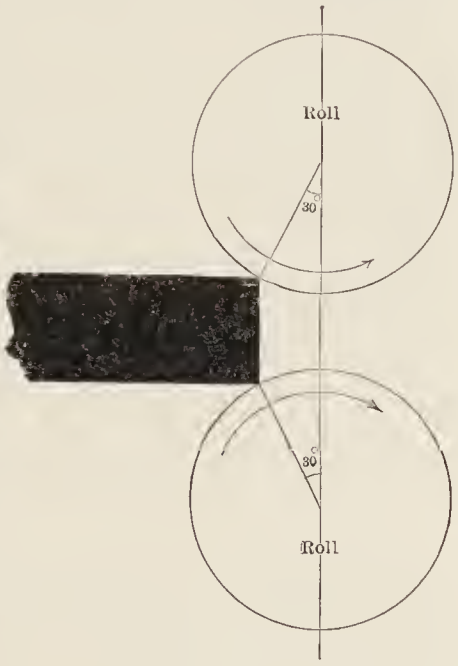


FIG. 140.

Speed of Rolls.—The more work the rolls do, the slower must they revolve, because the piece entering the train gives a shock to the mechanism that is dependent upon the power exerted and the momentum of the moving parts. Thus (1) the larger the pieces treated (2) the colder they are, and (3) the larger the rolls, the slower must be the speed. In America, speeds are at the high limit. Reversing slab-mills may do the work at 20 or 30 r.p.m.; three-high blooming rolls may run over 50 r.p.m.; mills for finishing rails, 100 r.p.m.; and rod mills from 550 to 1200 r.p.m.

Making of Rolls.—Cast-iron or steel rolls are cast in approximately the desired shape and then turned accurately in a lathe, being fitted exactly to a templet when completed. After rolling some thousand tons of material, they become worn and produce too large a size of finished shapes. They may then be used for a larger size of the same kind of article by putting them back in

[1] In America, the train that produces blooms (i.e., pieces of steel usually about 6 to 8 1/2 in. square) from ingots, is sometimes, but not always, known as "bloom rolls," or "blooming rolls," instead of cogging rolls; and the train that produces "slabs" (i.e., thick, wide, rectangular pieces that are to be rolled into plates) from ingots is known as the "slabbing-mill."

Screw down mechanism.

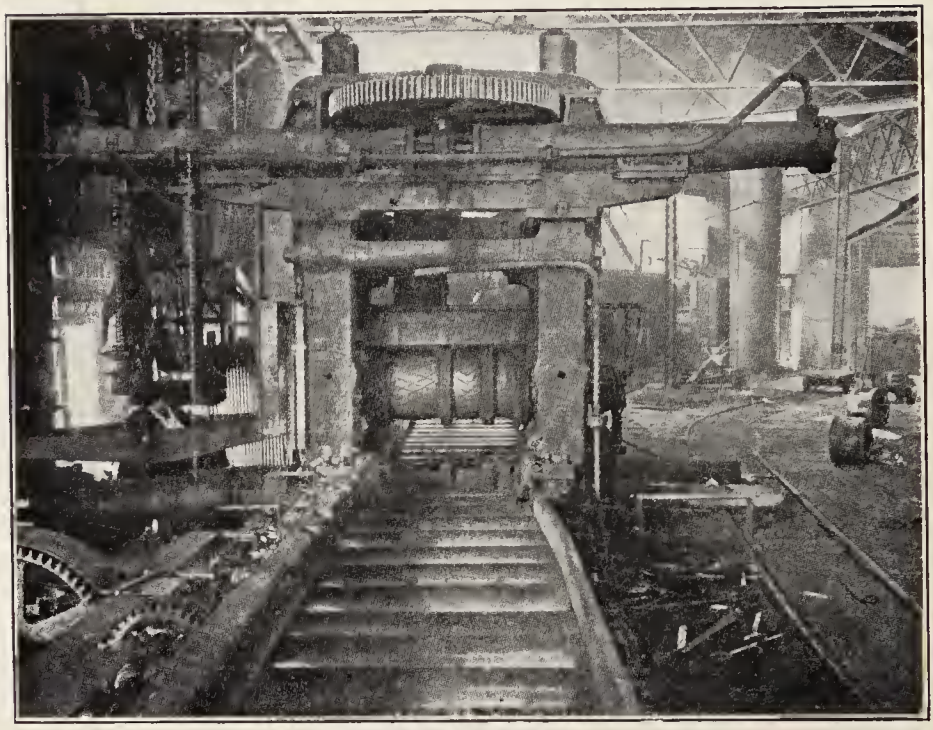


FIG. 141.—INDENTATIONS ON A COGGING MILL.

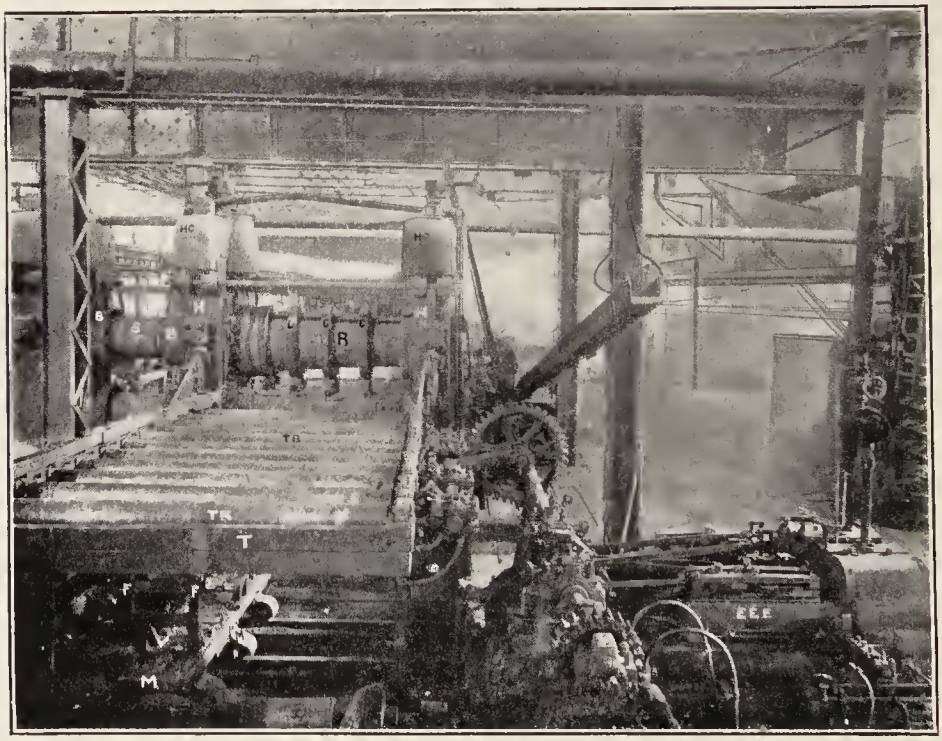


FIG. 142.

B, Coupling boxes, C, collars; EEE, rollar table engine; F, fingers, or horns on manipulator; H, housings; HC, housing cap; M, manipulator or "Go-devil"; R, roll; S, spindle; T, roll table; TR, table rollers.

the lathe and turning to another templet. For example, a roll for a 20-in. I-beam, with a certain thickness and width of flange, may be converted to one for a 20-in. I-beam with thicker web and longer flange.

The Mill.—The different parts of a rolling-mill may be seen in Fig. 142. The *wobblers* (Fig. 143) are made of the same cross-section as the spindle, some examples being shown in Fig. 138. The *coupling boxes* (Fig. 142) fit over the spindle and wobblers,

FIG. 143.

B, coupling boxes; C, collars; E, roll engine; G, guides; H, housings; S, spindles; TR, table roller; HC, housing cap; W, wobblers; TM, table motor.

so that neither can turn without the other. In some mills the coupling-boxes are made of cast iron in order that, if any shock comes upon the driving mechanism, the boxes shall give way and relieve the strain. In other mills the boxes are made of cast steel, as it is thought that the constant delays due to broken couplings are more costly than breakages in other parts of the mill. The *spindles* (Fig. 143) are at least twice as long as the coupling-boxes, in order that they may carry both of them at once when the train is uncoupled. Both boxes slip back upon the spindle.

Pinions (Fig. 144) are now usually made of steel for the sake of strength. *Housings* (Fig. 143) are made of either steel or of cast iron, depending on the strains to which they are subjected and the opinion of the manager. In America, they are usually

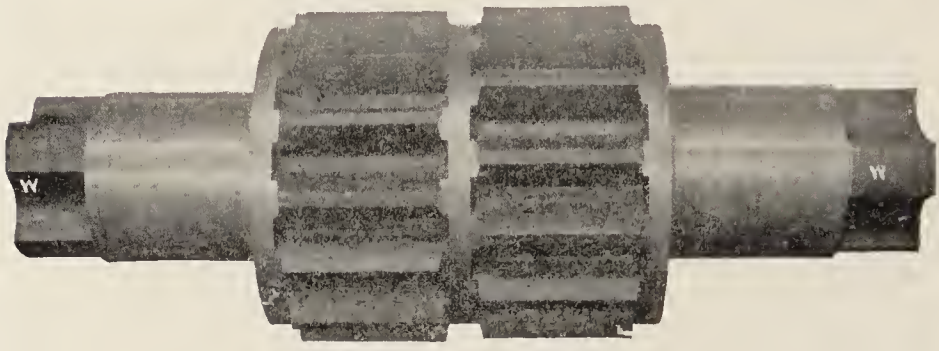


FIG. 144.—A PINION.
W = wobbler.

made so that the top can be removed and the whole train of rolls removed at once, together with the chocks, and several mills have spare sets of rolls all made up ready and carried in a sling, so that a new set may be dropped into place with a crane with the least possible delay to the mill. Delays in rolling-mills are very costly, because of the idle labor and capital, and because other parts of the plant may be delayed thereby.

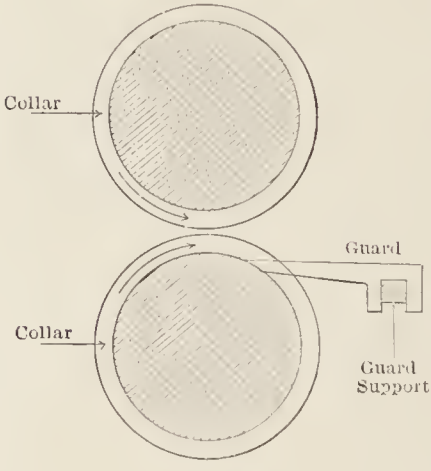


FIG. 146.

The *screw-drawn mechanism* (Figs. 141, 146) which adjusts the distance between the rolls is operated by hydraulic pressure or by electric motors. It is connected with a telltale gage which advises the roller exactly as to the distance separating the rolls.

Guards (Fig. 145) are of steel and serve to peel the piece off the roll and prevent it encircling the roll (called "collaring") in case it becomes wedged between the collars. They may be upon the lower roll, as shown in Fig. 146, or upon the upper roll, and counterbalanced to hold them in position, when they are called

"hanging guards." *Guides* (Fig. 147) are on the opposite side of the train, and assist in conducting the piece straight into the groove.

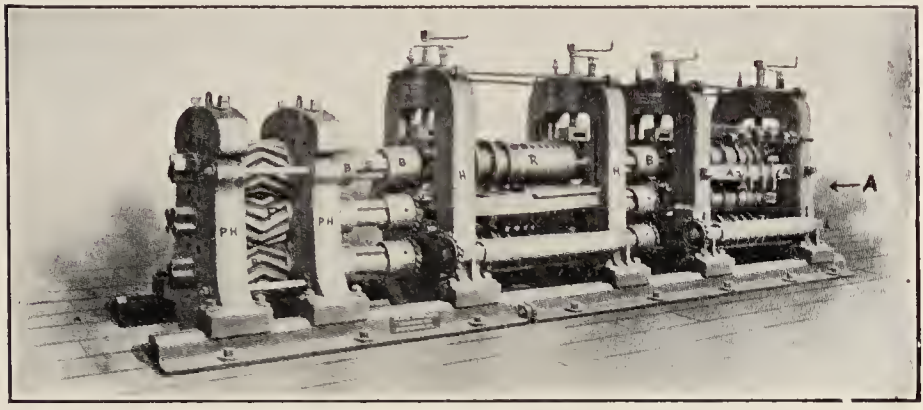


FIG. 146.
A, hanging guards; B, coupling boxes; H, housings; P, pinions; PH, pinion housing; R, rolls; S, spindles.

Roll Tables.—Heavy pieces are handled at the rolls by supporting them upon a series of rollers, situated in front of and

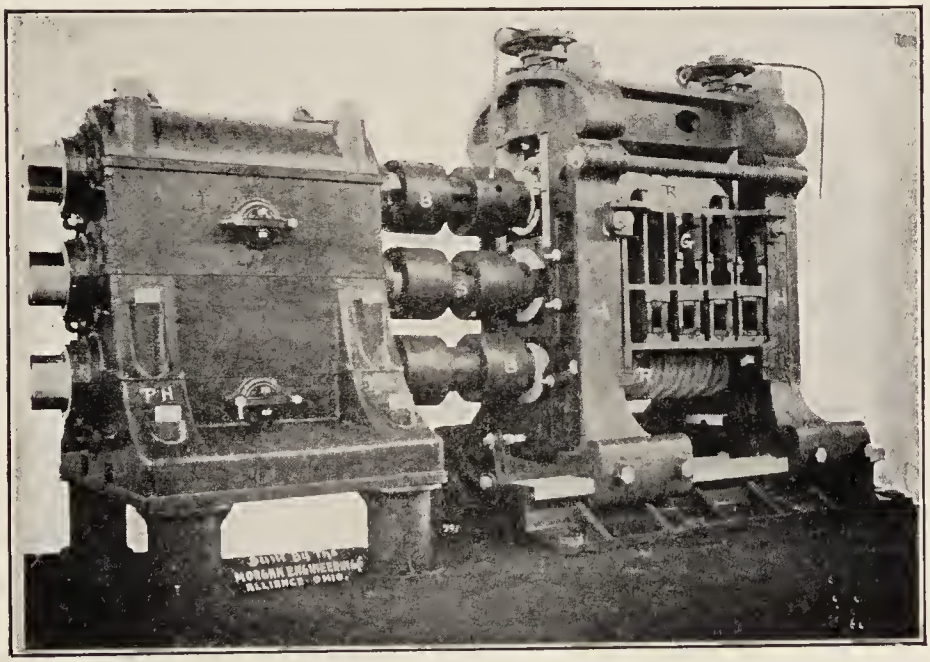


FIG. 147.
G, guides; HC, housing cap; PH, pinion housing; RR, rolls.

behind the roll train, and known as the "tables." (Fig. 148.) At two-high mills the tables are stationary; at three-high mills

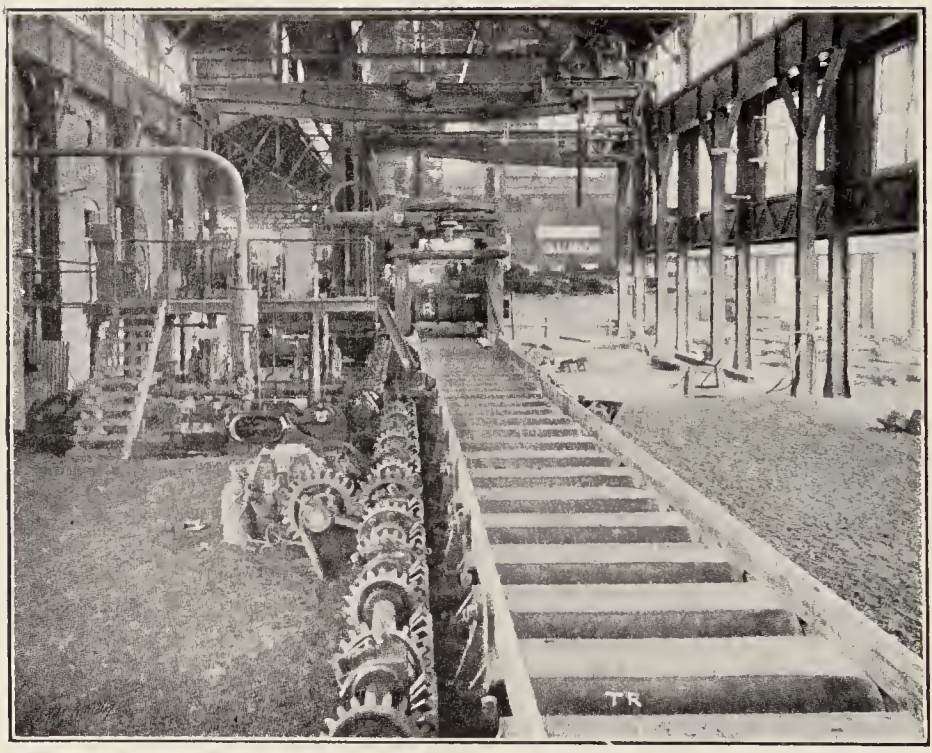


FIG. 148.

D, Screw-down mechanism; EEE, table engine; TM, Table motor; TR, table roller.

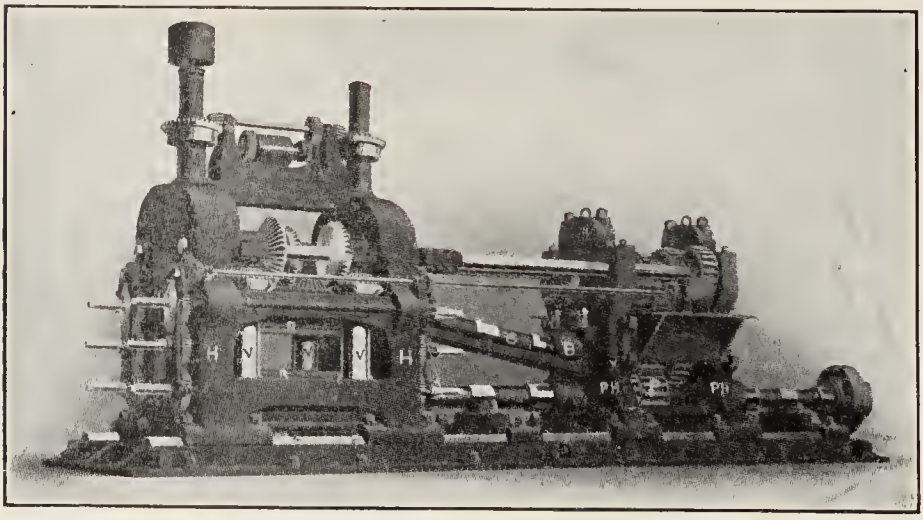


FIG. 149.—TWO-HIGH, REVERSING UNIVERSAL MILL.

VVV, Vertical rolls; RR, Horizontal rolls.

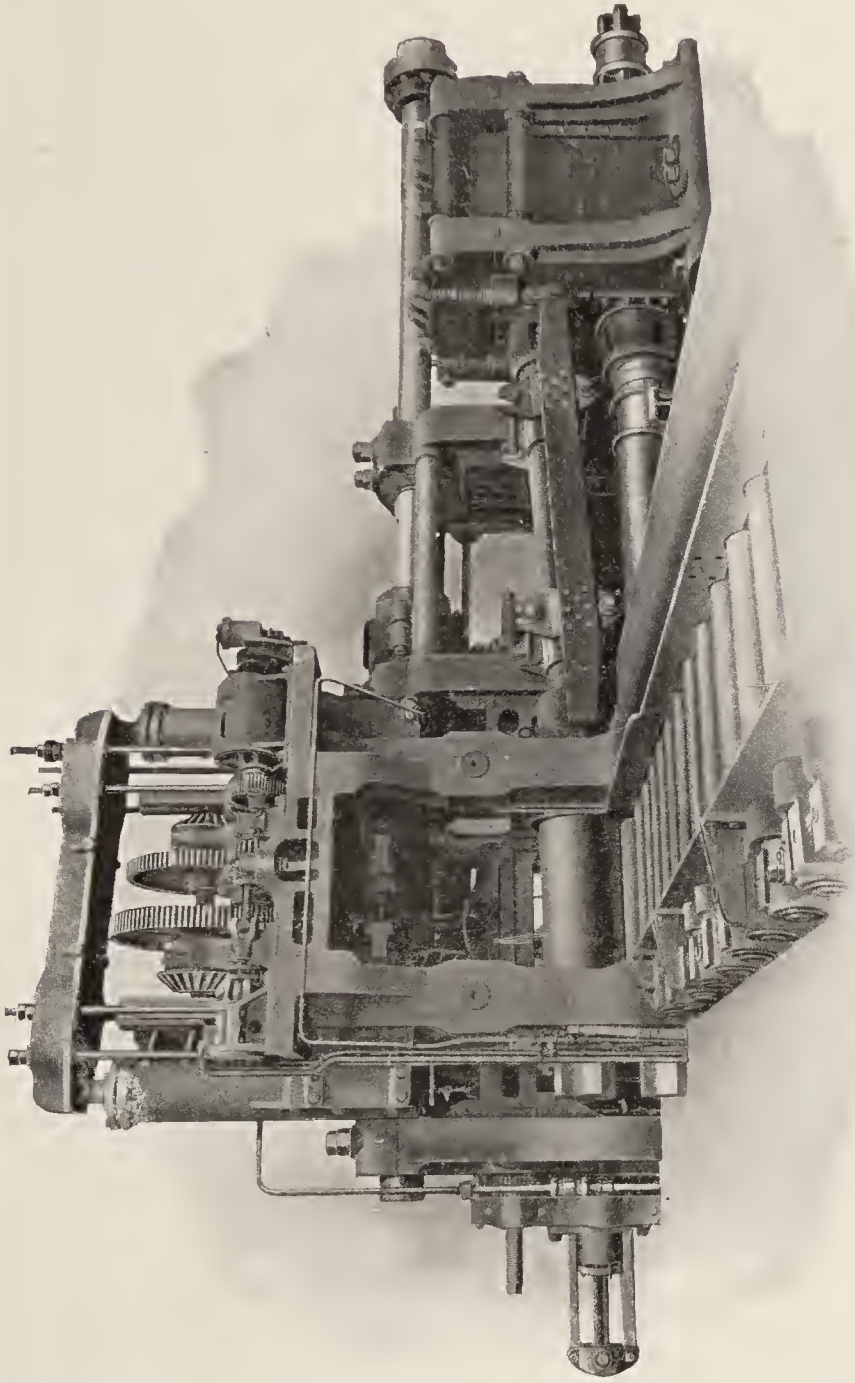


FIG. 150.—TWO-HIGH, REVERSING UNIVERSAL MILL WITH INDEPENDENT ELECTRIC DRIVE FOR VERTICAL ROLLS.

the front and back tables are sometimes raised and lowered together by hydraulic or electric mechanism, and sometimes they are pivoted near the middle, so that the end next the rolls can be tilted upward in order to bring the piece between the guides which direct it into the groove. The rollers to handle large pieces are "live," that is, they are made to revolve by electric motors and thus move the piece back and forth. "Dead" rollers are used where pieces are to be moved by hand.

Transfer Tables.—Roller tables are sometimes made so that they may be moved bodily from one roll train to another, carrying the piece of metal with them, and so connected electrically that the roller can be caused to revolve when the table is in any location.

Manipulators (Fig. 142).—If two or more posts, supported on a carriage which can be moved laterally, project between the rollers of a table, their sidewise motion will transfer the piece from one pass to another. If the table is of the lifting type, the posts, or "horns," or "fingers" can be brought to such a

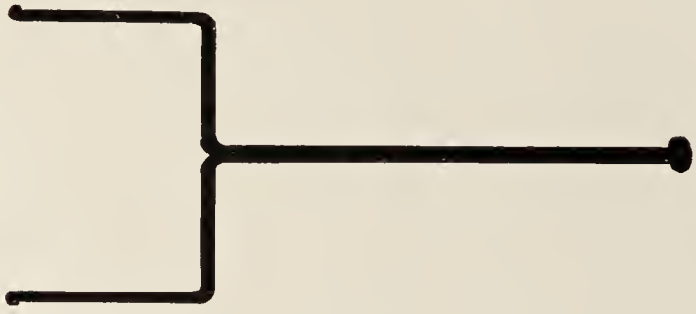


FIG. 151

position that the lowering of the table will bring the edge of the piece upon the horns and thus tip it on to the other side. This form of manipulator is much used at three-high blooming rolls, and is very efficient and rapid in its work. The same type is used at reversing blooming rolls, but the piece is more usually tipped over by the roller with the tool shown in Fig. 151.

Roll Engines.—The service on rolling-mill engines is very severe, because the full load comes upon it when the piece enters the rolls, and then leaves it as suddenly again. To equalize these sudden variations of power, all but the reversing engines are built with very large and heavy fly-wheels and run at a high rate of speed (from 30 to 250 r.p.m.), with governors of a quick-acting

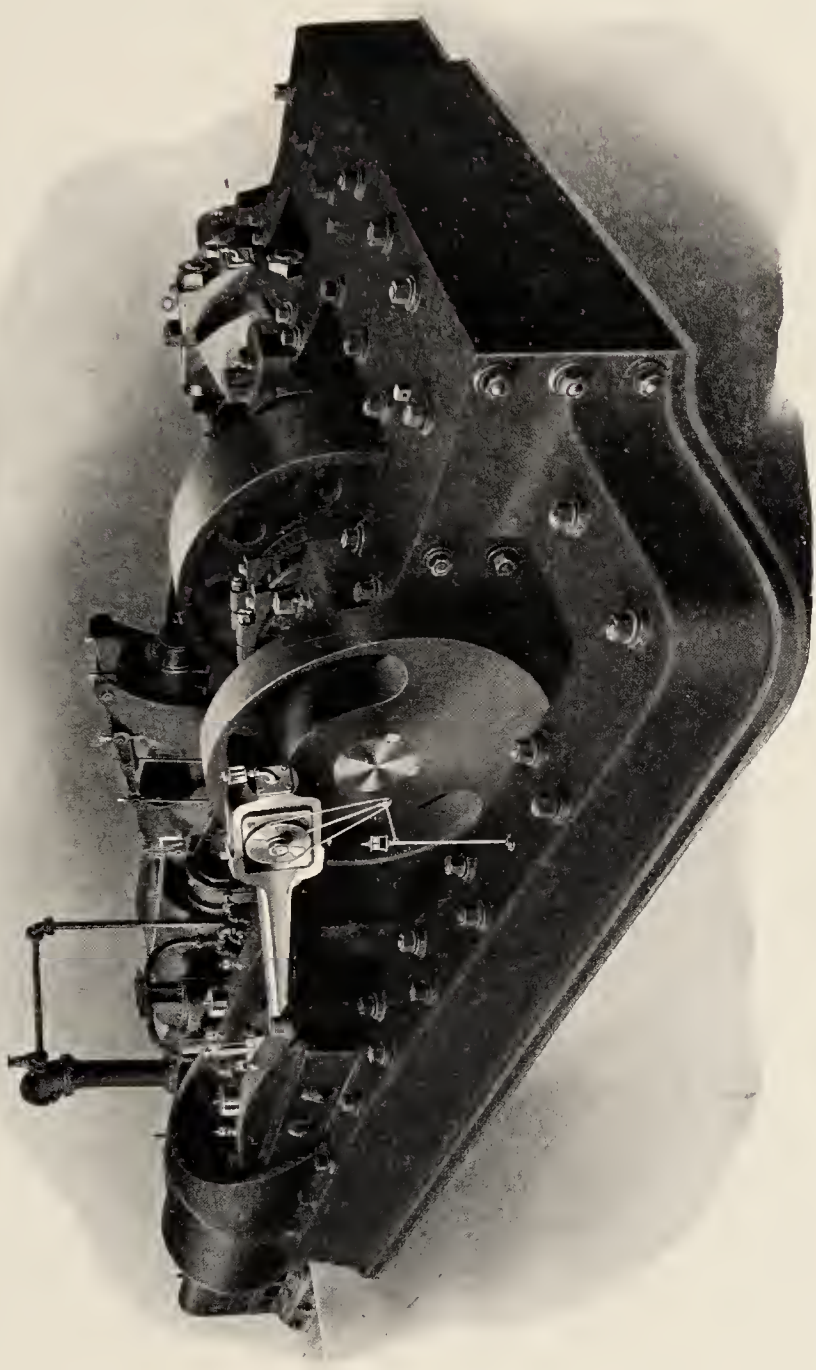


FIG. 152.—REVERSING ROLLING MILL ENGINE.

type. The Allen engine with the Porter governor serves these purposes, and the Porter-Allen type is much used. The ordinary slide-valve is used on the smaller engines. Corliss valves are commoner in America for engines doing heavy work (1000 to 3500 H. P.,

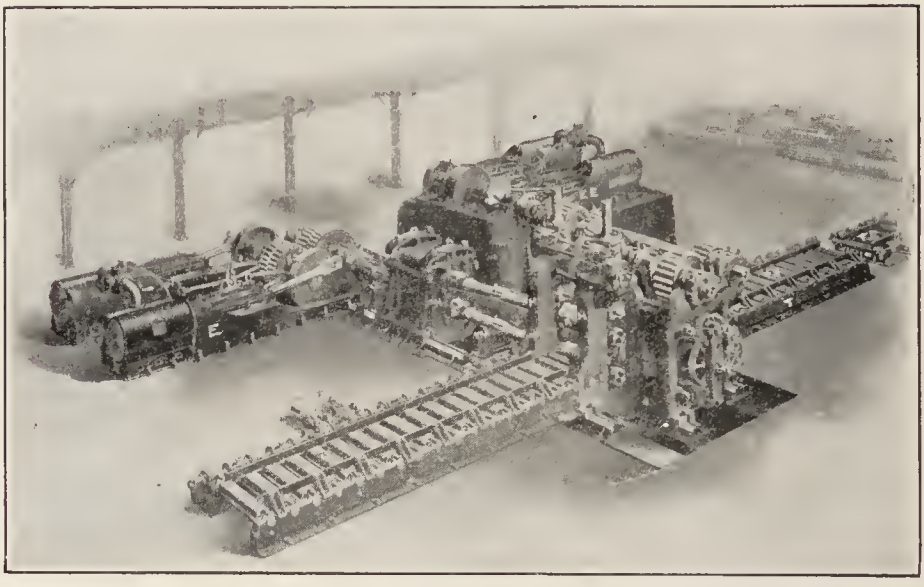


FIG. 153.—UNIVERSAL MILL.

E, Engine for horizontal rolls; EE, engine for vertical rolls; EEE, roller table engine; TT, roll tables; TR, TR, table rollers.

while piston-valves are favored in England. The fly-wheel is placed upon the crank-shaft, to which the roll train is directly coupled. The fly-wheels very exceptionally weigh as much as 75 and 100 tons or more.

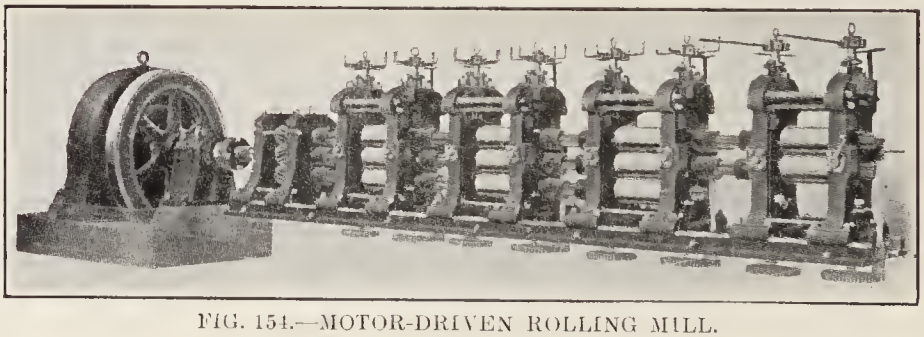


FIG. 154.—MOTOR-DRIVEN ROLLING MILL.

Piston-valves are used almost always for reversing engines which are compounded, so they may never come to rest at a dead point. There is, of course, no fly-wheel, and the engine is directly

coupled from the crank-shaft to the roll train in the large American mills, but is geared down so that the engine can develop a higher speed than is desired for the rolls, thus requiring less power. Reversing slabbing-mill engines have capacities up to 25,000 H.P. each.

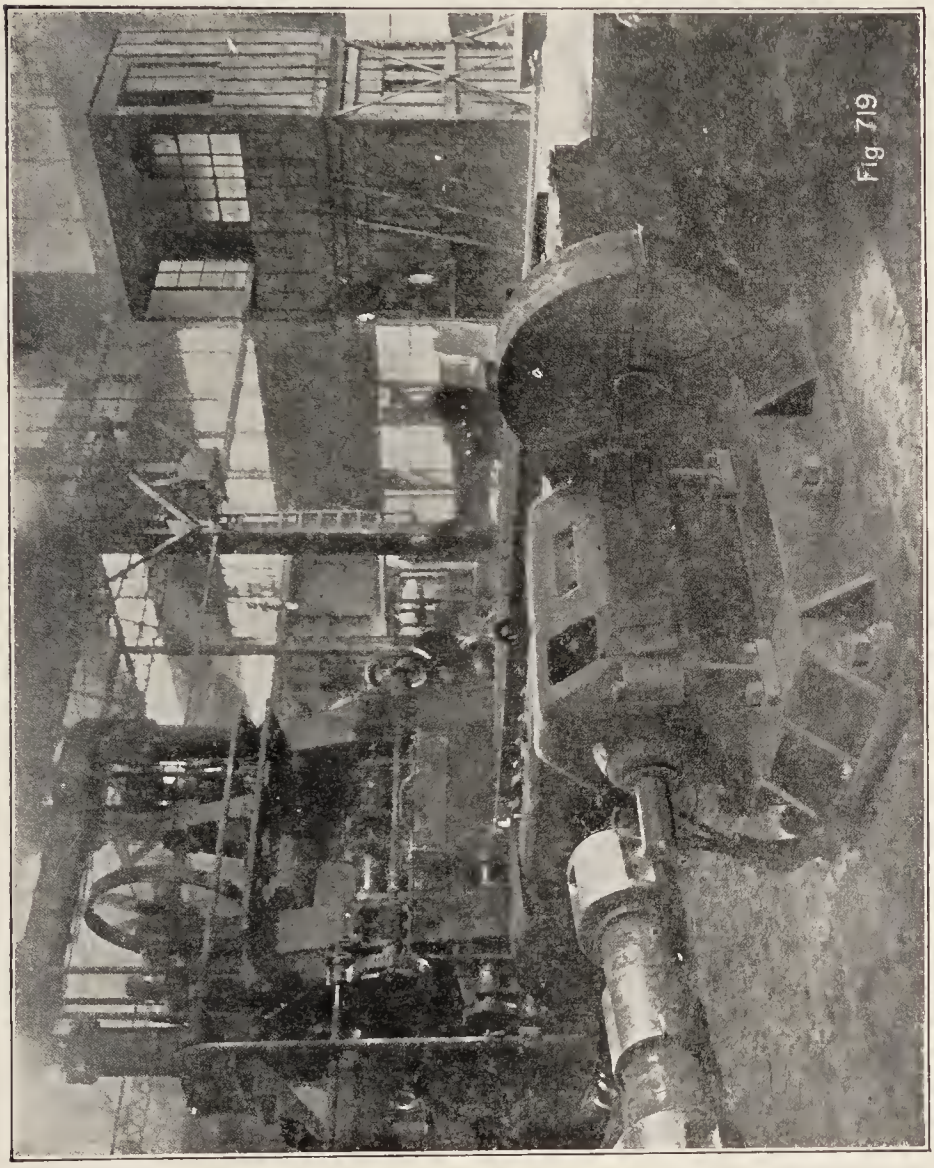


FIG. 155.—ELECTRIC TABLE MOTOR.

Electric-motor Drive.—In many mills in America and Europe electricity has replaced steam for all power purposes. The advantages of electricity over steam are a lower operative cost, greater security of operation, fewer breakdowns, and a more

flexible relation between the prime mover and the load, the result of the electric motors receiving a sudden shock more elastically. On the other hand, the advantage of steam, is that, although it receives the load less elastically, it adjusts itself

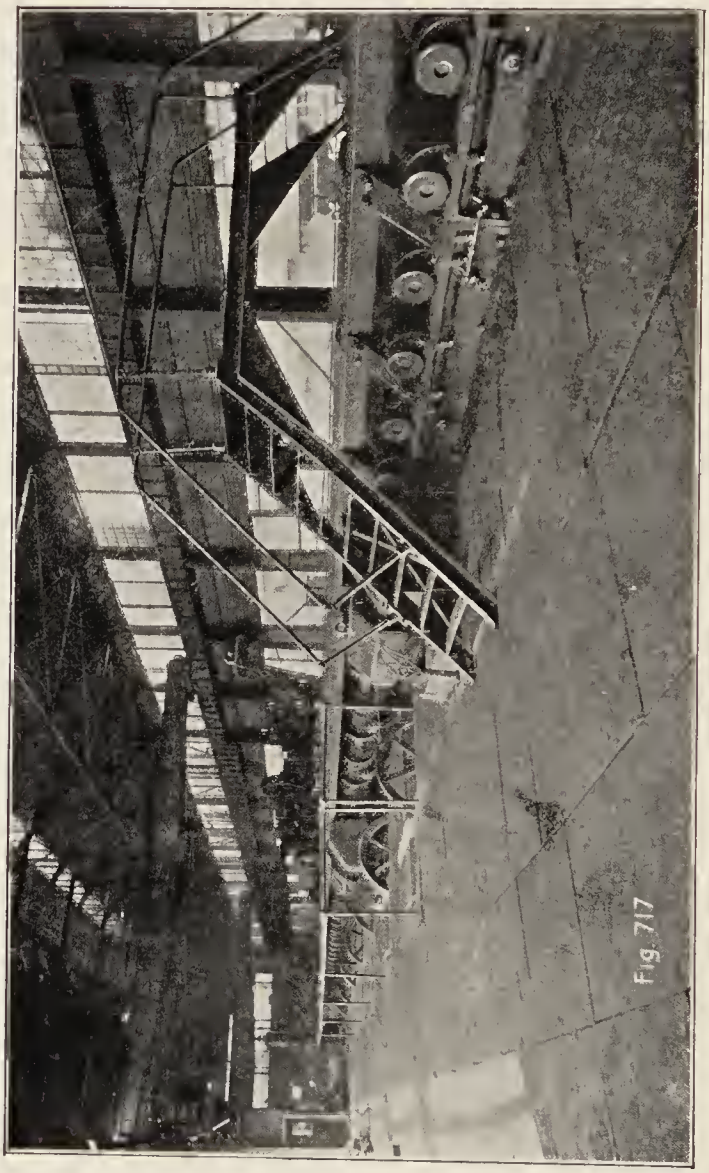


FIG. 156.—TABLE DRIVEN BY ELECTRIC MOTORS.

quicker and better to the extreme variations in load that always occur in rolling-mills. This is especially true of reversing mills.

As already noted, the smaller the mill the less will be the load, and therefore the variation in load. Consequently, in England, Sweden and Germany there are many motor-driven roll trains of

the smaller size, and a few up to several hundred horse-power, including one reversing motor of 1200 H.P. Even large mills are now most commonly operated by electric power, if of recent installation, and this applies even to reversing mills. One reason for the extent of this change is of course the cheapening of the cost of electricity due to the better utilization of the waste power of blast furnaces at large plants by the installation of gas engines.

Rolling-Mill Practice

Troubles in Rolling.—There are more difficulties met with in rolling-mill practice than we can discuss here, but it may be said that the seriousness of the difficulty is estimated almost altogether in proportion to the delay it causes in the operation of the mill, rather than in the loss of a small amount of material or of a part of the mill itself. For example, the breaking of a table engine, roller, or even a roll, is regretted more because of the time necessary to put in a new one than because of the loss of the part. This is one reason why electric motors to operate the tables have, in many cases, replaced small steam engines. The same conditions have also resulted in different parts of the mill being made interchangeable. In many mills it is customary to have spare table engines, or motors, etc., always ready, and the least accident to one of these machines would result in its being immediately replaced by a whole new one.

The most important common troubles in rolling-mill operations, probably, are: (1) Bending and breaking of the rolls, due to their being placed under too severe a strain, either because the draft is too heavy or because the piece is cooled too much, (2) fins caused by metal being squeezed out between the collars of the rolls, as shown in Fig. 157; these fins, besides spoiling the material, are liable to break the rolls; (3) collaring.

FIG. 157.—FIN.

Rolling Plates.—In the rolling of plates an ingot, usually of open-hearth steel and weighing 2 to 10 tons, is first cogged down in the slabbing-mill, producing a long, flat piece of metal. The slabbing-mills are frequently of the two-high, reversing, universal type. The front end of the piece is cut off in a huge hydraulic or electric shear to remove the pipe and then it is cut up into slabs of the desired size or into slabs of a size such that each one will make one plate. The slabs are then transferred to the

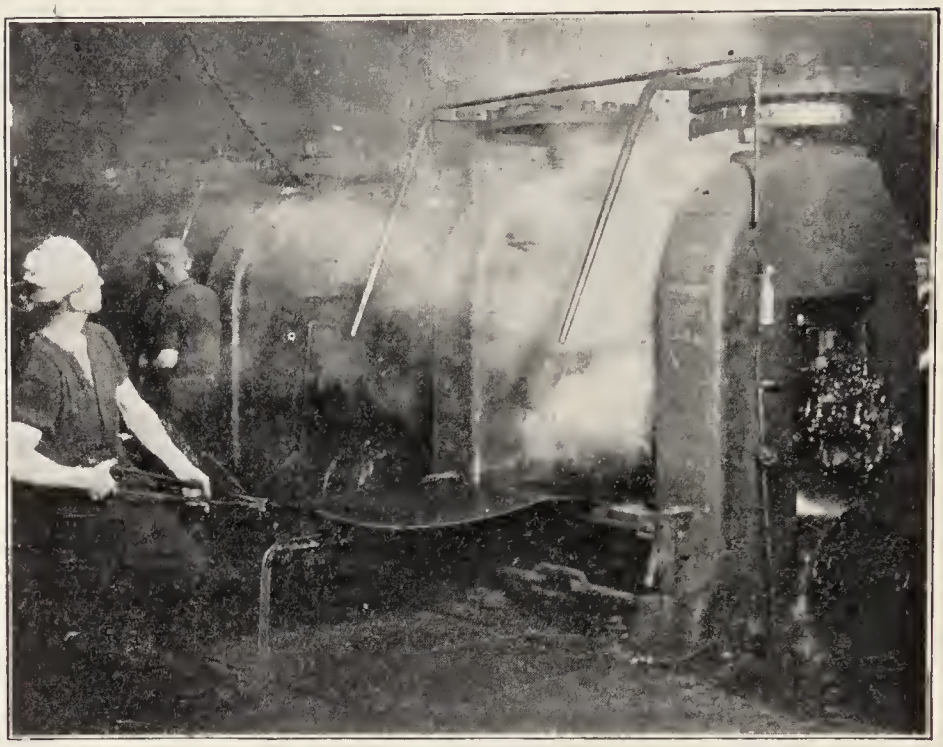


FIG. 158.—TWO-HIGH PLATE MILL.

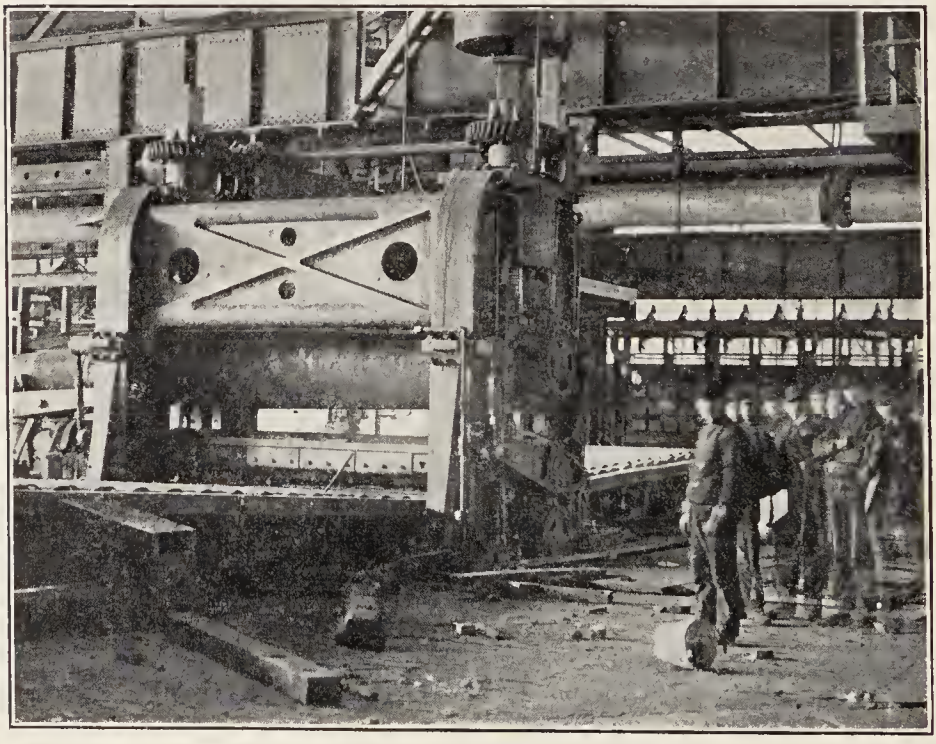


FIG. 159.—THREE-HIGH PLATE MILL.

heating furnace, heated to about 1300° C., and rolled in a three-high or, more rarely, a two-high reversing plate-mill, in some cases there being a pair of vertical rolls to keep the edges straight. During the rolling a shovelful of salt is occasionally thrown upon the surface of the plate, which carries in between the rolls some

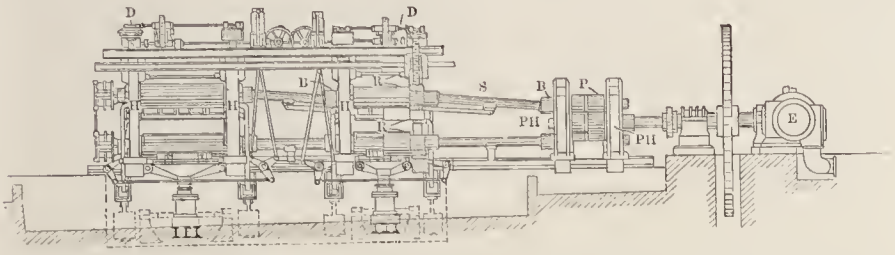


FIG. 160.—THREE-HIGH PLATE MILL, TWO STANDS OF ROLLS.
B, Coupling boxes; D, screw-down mechanism; E, roll engine; H, housings; P, pinions; PH, pinion housing; RR, rolls; S, spindles.

of the water which is always trickling over them to keep them cool. Sand may be used for the same purpose, and in England heather is sometimes used. As soon as this water is pressed against the hot plate it is converted into steam, causing a rapid series of explosions which blow the scale off the upper surface of

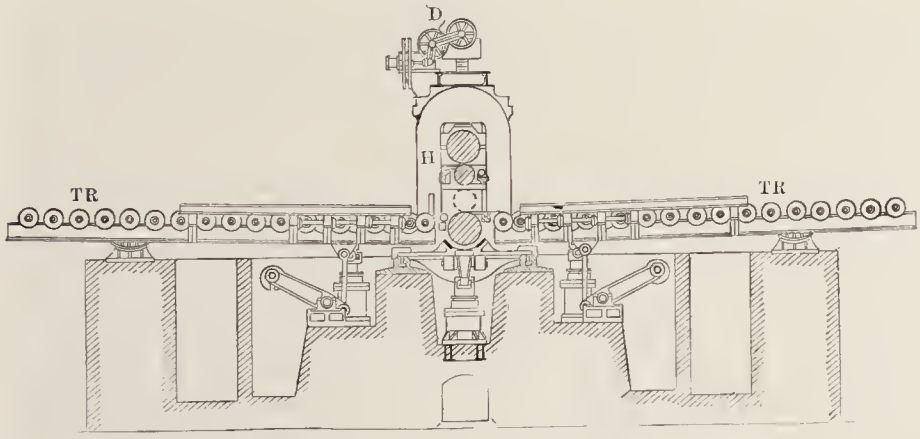


FIG. 161.—OTHER VIEW OF FIG. 160, SHOWING METHOD OF RAISING THE ENDS OF THE TABLES NEXT TO THE ROLLS.

the plate and give it a smoother finish. As the process continues, the operator tests the thickness of the plate with a gage, and when it is of the desired thickness, it is passed up to the straightening rolls and then to a cooling table, being marked with a distinguishing mark on the way to indicate the heat of steel from

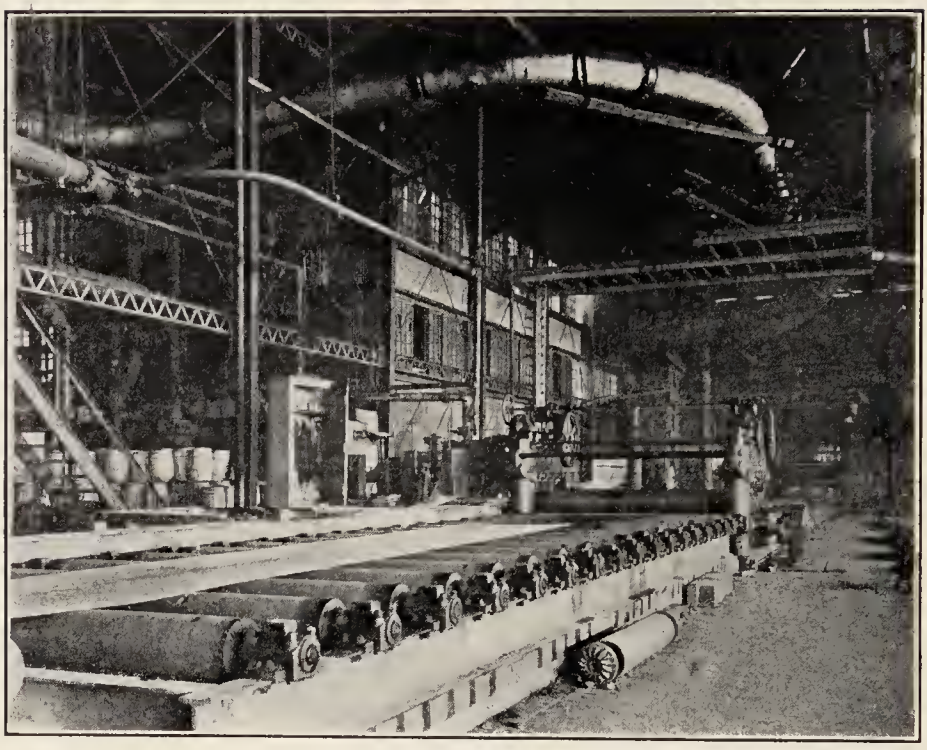


FIG. 162.—PLATE STRAIGHTENING ROLLS.

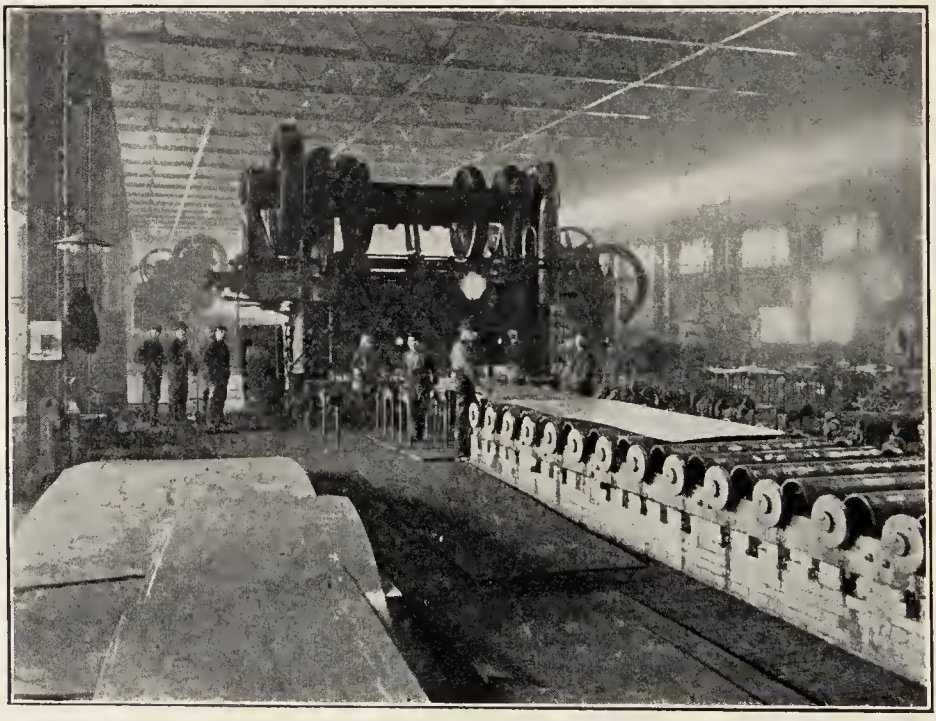


FIG. 163.—PLATE SHEARS.

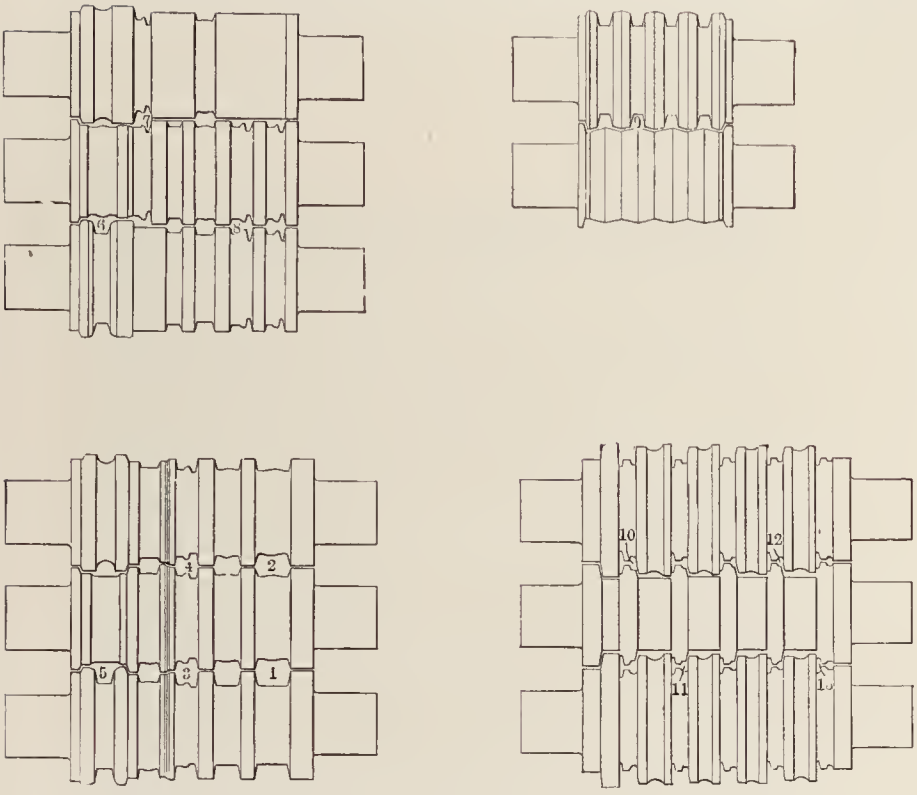


FIG. 164.

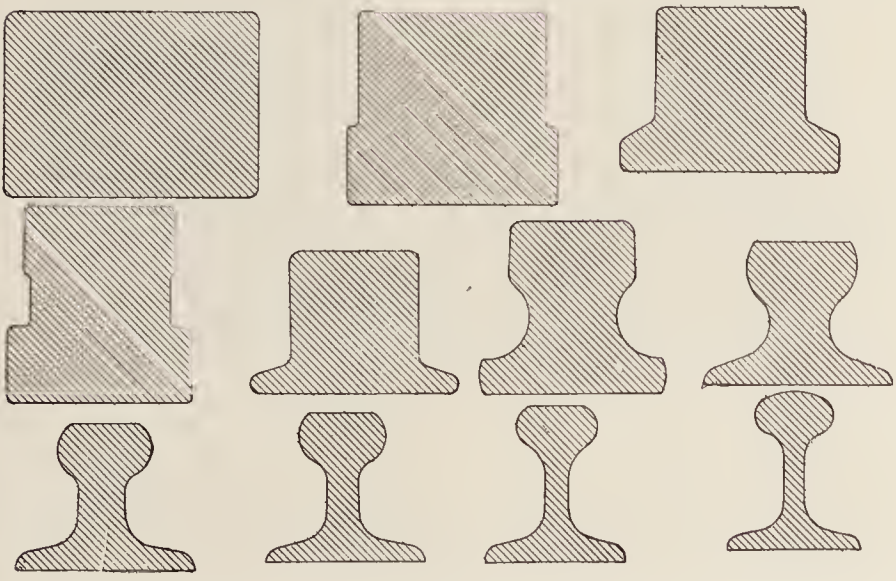


FIG. 165.

which it was manufactured. When cooled it is sheared to the desired size and shape. The weight of finished plate will probably be not more than 80 per cent. of the weight of the steel sent to the rolling-mill in the form of ingots.

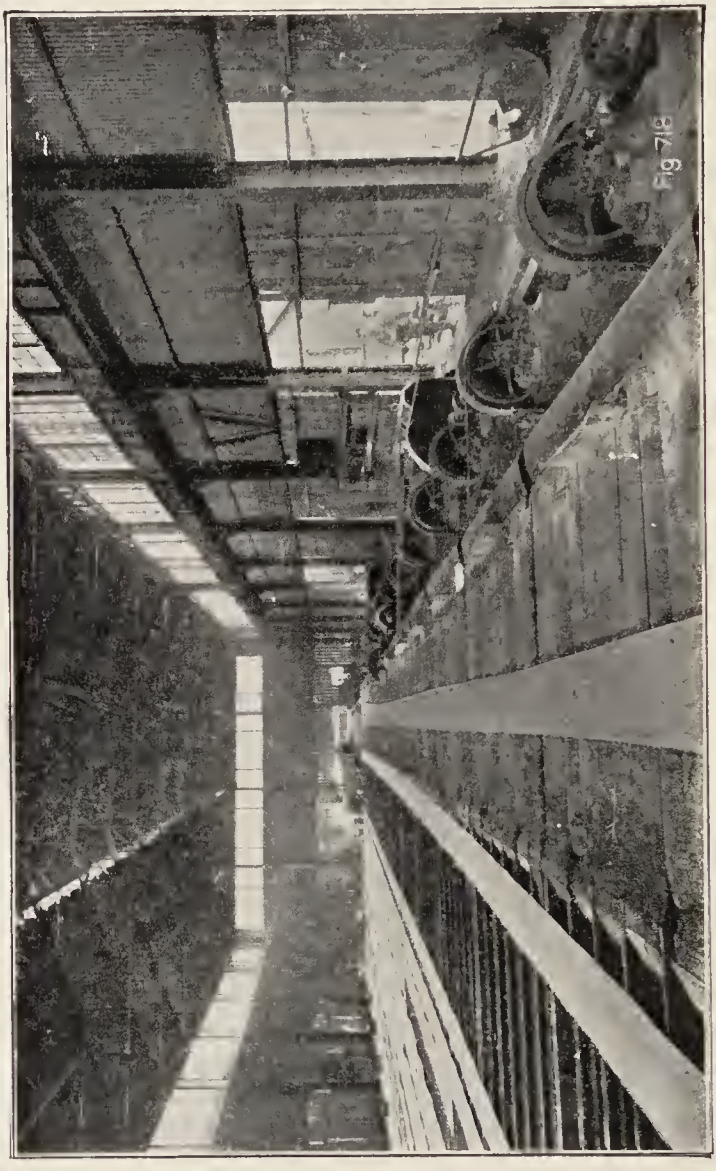


FIG. 166.—SKELP ON A COOLING TABLE.

Rolling Rails.—An ingot of about 3 tons in weight is sent to the rolling-mill, where it is kept in the heating furnace for 50 minutes or more until the interior is entirely solid and it is of a uniform temperature throughout. It is then rolled into blooms, either in a three-high mill, such as shown in Fig. 142,

or in a two-high reversing mill. In the three-high mill, an ingot 18 1/2 in. square at the middle (tapering about 1/8 to 1/4 in. to a foot in order that the mold may be more easily removed) will be reduced to a bloom of about 8 in. square in nine passes, the amount of reduction in each pass being about 12 to 18 per cent. of the original area. The top end is then cut off to remove the pipe, the bottom end to remove the irregularity due to

FIG. 167.

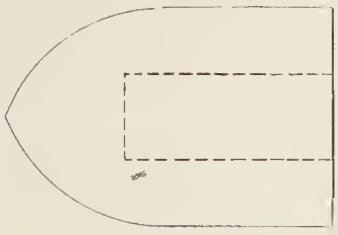


FIG. 168.—MANDRIL.

the rolling, and the piece cut in two to make two blooms. The blooms are then generally reheated in a heating furnace and passed through the series of changes shown in Fig. 165, until they have assumed the proper size and form, the greatest amount of draft being usually not more than 22 per cent., except upon the middle

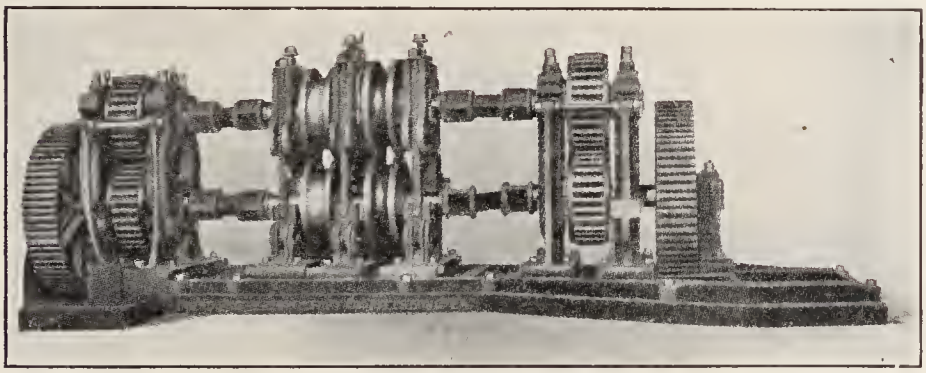


FIG. 169.—PIPE-WELDING ROLLS.

portion of the web. In some cases the blooms are not reheated, but go directly from the bloom rolls to the first roughing train. This makes the metal crack more in rolling, however, and these cracks will ultimately show as a mark on the finished product, which causes the rails to be classified by the inspector in the second or third class. Railroads will accept only 5 or 10 per cent.

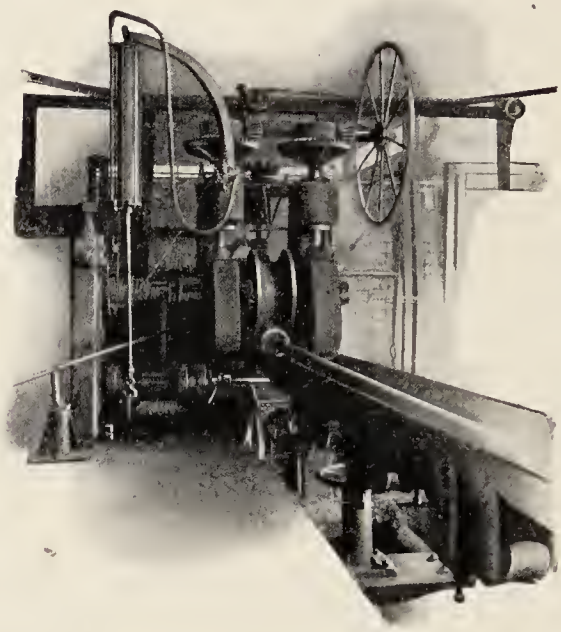


FIG. 170.—PIPE-WELDING ROLLS WITH MANDRIL IN POSITION.

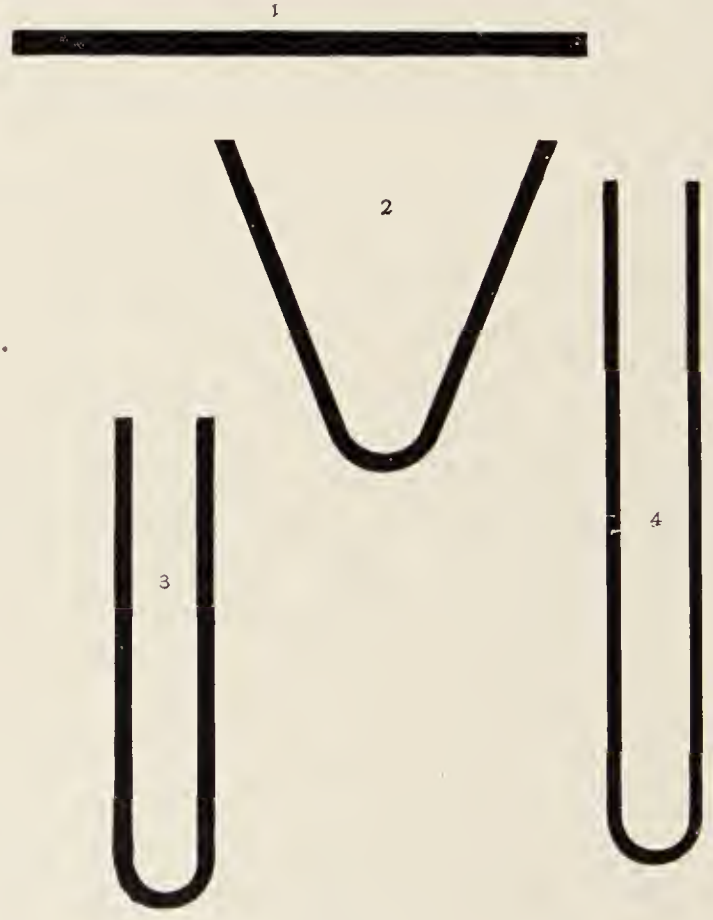


FIG 171.

of their order in second-class rails, while third-class rails are not acceptable and must go into the tracks of the steel company itself or else be reheated and rolled into smaller sizes, whereby the marks will often be eliminated. If the blooms are reheated before going to the roughing train, many of the cracks formed during blooming will be seemingly closed up, or in any event will not show. Furthermore, if this reheating is to take place, the ingots need not be heated so hot in the first instance, and therefore will not be so tender and so liable to crack.

Making Lap-welded Tubing.—The wrought iron or steel low in carbon is first rolled out into skelp about 20 to 25 ft. long, and of a width a little more than three times the intended diameter of the tube. The skelp if large is then rolled up into a rough form of a pipe, as shown in Fig. 167, by passing it sidewise through rolls, which bend it roughly to the shape of a pipe, with edges overlapping. The same is done in the case of small 2- to 8-in. tubes, by drawing them through a die. It is then passed at a welding heat through a pair of rolls, with the seam that is to be welded upward. Between the rolls is a mandril on the end of a long rod and of the size of the inner diameter of the tube (Fig. 168). The rolls press the two parts of the weld together over the mandril, and the pipe, after another rolling to give true size and after straightening and testing, is ready for service.

FIG. 172.—SECTION OF BELL.

Making Seamless Tubes.—Seamless or weldless tubes are made either by distorting a steel plate between dies, as shown in Fig. 171, or else by piercing a hole through the center of a hot steel billet and then rolling it successively between rolls over a mandril. The hole is sometimes first of small size and then expanded by pressing larger and larger expanders through it. The pierced billet is then rolled over mandrils constantly decreasing in size until the inner and outer diameters are brought to the desired size.

Butt-welded Tubes.—Butt-welded tubes are made by heating the skelp to a welding temperature and then drawing it out of the furnace through a bell, as shown in Fig. 172, which curls it up and welds the edges together, without lapping. Butt-welded tubes are not so strong as lap-welded tubes, and are not usually used for boilers or high pressures, or where they will be expanded much by heat during service. They are mostly made in the small sizes.

Wire Drawing

Wire is a product formed by being drawn cold through a die. The commonest shapes are "rounds," and the next, hollow tubes, but a great variety of forms may be produced at will.

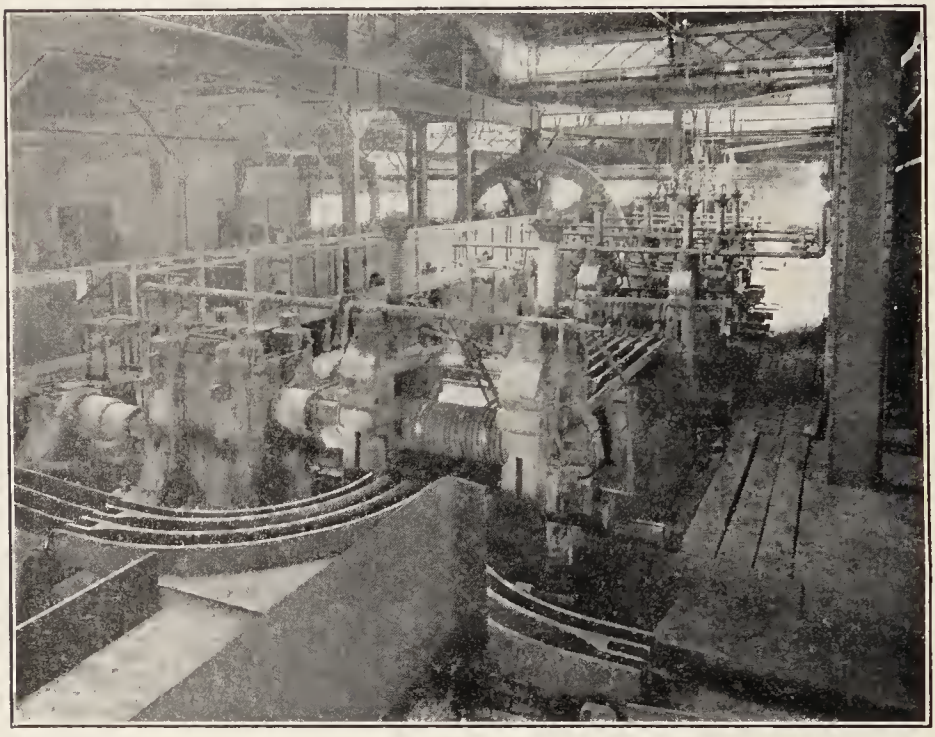


FIG. 173.—WIRE ROD ROLLING TRAIN.

These mills will roll steel down to from 7/8 to 1/2 inch rods, which are then drawn into wire.

FIG. 174.—WIRE ROD FRAME.

Effect of Drawing.—The effect of the drawing is to produce a vey exact size of material and to increase the strength, hardness, and brittleness of the metal. In the drawing of steel, the crystals

of the metal are actually pulled apart and flow by each other, the outer layers of the metal being dragged back over the central core, there being at the same time a pressure exerted in all directions toward the center, which results in a certain amount of backward flowing even there. Because the crystals are so broken up during the operation, and because the metal is never heated above its critical temperature during annealing, the grain of the steel is very fine and the crystals are intimately mixed, which is probably the cause of the great strength of wire.

Annealing.—With each draft the wire becomes harder and more difficult to draw. As it is pulled through the die by a force equal to 40 to 80 per cent. of its tensile strength, it is necessary to soften it at intervals by annealing, lest it break. The annealing is accomplished by enclosing the wire in some receptacle that protects it from oxidation and then heating to a low-red heat. In the case of steel, it is required after every eight to three passes, depending upon the amount of carbon in the metal and the amount of "draft"; i.e., proportionate reduction in size.

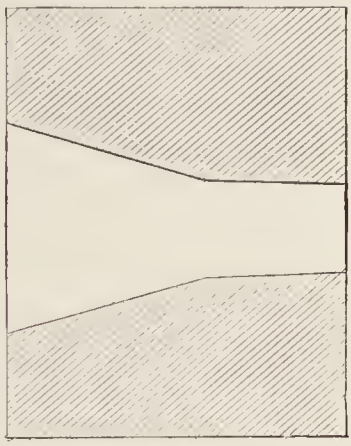


FIG. 175.—SECTION OF WIRE DIE.

Dies.—Wire dies are usually made of high-carbon steel (say about 2 per cent.), through which a tapered hole is made, as shown in Fig. 175. The object of using this material is that, as it becomes worn in service, it can be reformed and used for larger sizes, which could not be done with white cast iron.

Bench.—A "bench" on which wire is drawn consists of a reel which holds the coil of undrawn wire, a die support, and a second reel which draws the wire through the die and coils it up, and which is driven by bevel gears. The die rests against the support, and the wire, having a tapered point, is thrust through the hole and grasped by a pair of tongs, which pulls it out until it can be attached to the reel. This is then set in motion and draws the wire through. The die-holder is heaped up with lubricant of some kind, in order that the metal may pass more easily through the hole. The speed at which wire is drawn will vary from 75 to 750 ft. per minute, depending upon the size and

hardness of the material drawn and the amount of reduction during each draft. In many cases there is more than one die, and the wire passes successively through two, three or more, being constantly reduced in each one. Between each pair of dies is a reel, around which the wire passes two or three times, since the strength of the wire emerging from the last die would not be sufficient to draw it through all of the holes.

Draft.—The heavier the draft the greater is the hardness produced in the wire and the greater the wear of the dies. The average amount of draft will probably be from 20 to 25 per cent.

Drawing Tubes.—Hollow wire or small tubes are drawn sometimes over a mandril. This mandril may be a wire of about the size of the inner diameter of the finished tube. After several drafts, the tube is wedged so tightly on the mandril that it cannot be separated. It is then given an unbalanced squeeze between a pair of rolls, so that the tube is reduced in thickness, whereby its diameter is increased and the mandril may easily be withdrawn.

Pressing

Steel may be pressed either hot or cold, the latter method being used chiefly for thin and soft steel, and the former for very large work, such as armor-plate, cannon, etc., for which hydraulic presses have now largely replaced the heaviest steam-hammers.

Effect of Pressing.—The effect of pressing upon the metal differs from hammering, in that its action extends deeper into the material, thus giving a somewhat superior texture to the interior. Tests cut from the center of large pieces forged under the press are very much superior to those cut from the same place in pieces forged under the hammer.

Hot-pressing.—Presses vary in size usually from 600 to 14,000 tons. They may be either of the continuous or of the intermittent type. In the latter, the amount of pressure exerted increases step by step as the work progresses. The amount of work that can be done by the press in large-sized pieces is greater than that done by hammers for the same amount of power used. This results in a double saving of fuel, since more work can be accomplished with one heating. By means of the 10,000-ton

press at the Homestead Steel Works, a 50-ton armor-plate has been reduced 2 in. in thickness and moved forward 6 in. for each squeeze, while a 3000-ton press at the Firths Works in England has reduced a 30-ton ingot from 49 to 28 in. diameter in 30 minutes, and from 51 to 26 in. diameter in 65 minutes. Small

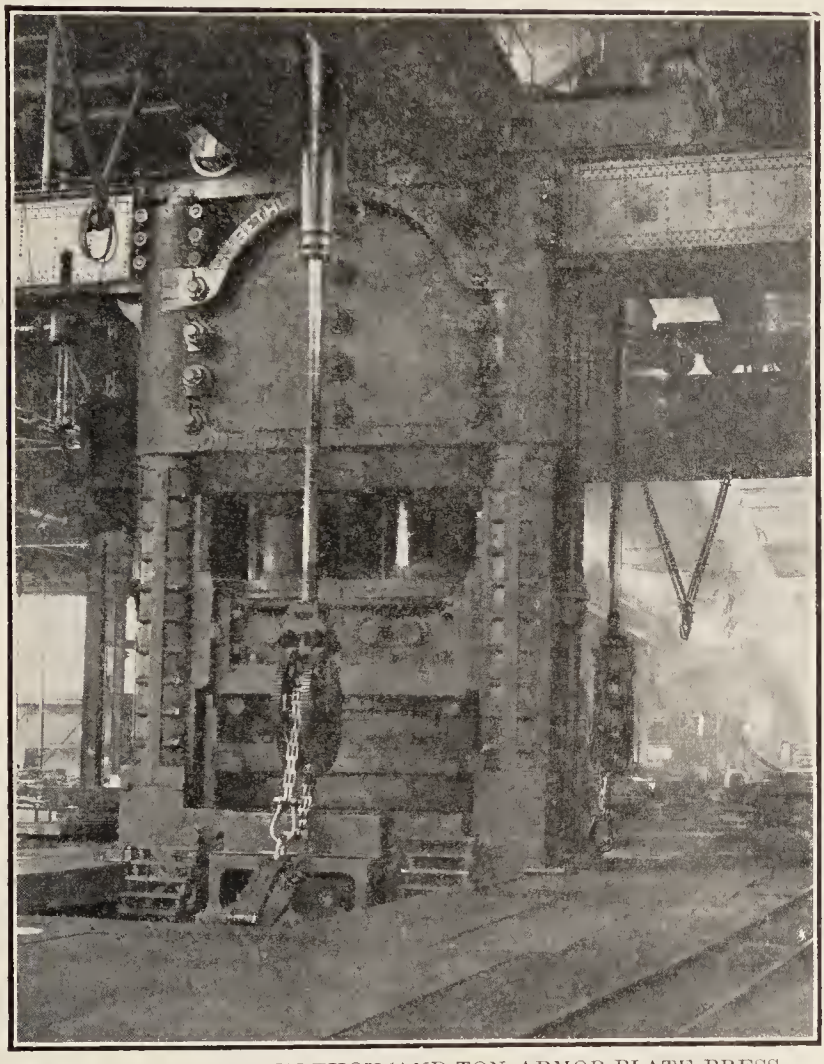


FIG. 176.—FOURTEEN-THOUSAND-TON ARMOR-PLATE PRESS.

pieces can, however, be turned out a little faster under the hammer.

Cold-pressing.—Thin plate for steel railroad-car construction, and many other purposes, is often formed by pressing it cold between dies under hydraulic presses of from 30 to 800-tons capacity. In this way bolsters, braces, and many other parts

are formed with great economy. Sometimes two or three presses are required with different dies to complete the shaping, and occasionally it is necessary to press some of the work hot, because the distortion is so great that the steel would otherwise be torn. Cold-pressing is also known as "flanging." It has one great difference from hot-pressing, in that there is no reduction in the sizes of pieces treated.

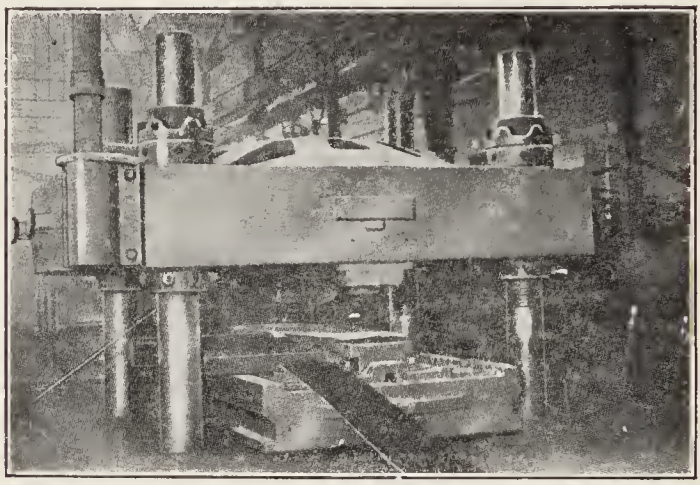


FIG. 177.—DROP-FORGING PRESS FOR PLATES.

Comparison of Mechanical Methods

Hot-working with Cold-working.—Cold-working gives greater strength, a harder material and more accurate finish as to size than any form of hot-working. Furthermore, it produces a finer grain on the surface of the metal. If the cold-working is followed by annealing at a temperature below the critical range of the steel (see pages 290 to 293), the material retains its fine grain, and is stronger and more ductile in proportion than metal that has been worked hot. Before cold-working the metal is pickeled in dilute sulphuric acid to remove the scale, and is therefore produced with a bright surface which is suitable, without machining, for use as shafting, for nickel-plating, etc. The annealing is usually effected inside closed vessels, in a reducing atmosphere of illuminating gas or some similar medium, which prevents the formation of scale. Cold-rolled steel is used for shafting and for articles that are to be drawn or stamped to shape—watch and clock springs, hack-saw blades, corset steels,

etc. Cold rolling, wire-drawing and "flanging" are the commonest forms of cold-working.

Hammering, Rolling and Pressing Compared.—Of all the mechanical methods, rolling gives by far the largest output per day, per unit of power, and usually per unit of fuel for heating. It is therefore the cheapest method, especially for labor. It does not work the metal as well as either hammering or pressing, both of which produce a much better crystalline structure, beside affording a better control of the temperature at which the operation is ended. Pressing works the metal at greater depths than hammering, and is therefore especially advantageous for producing large pieces. In such large pieces the size of the hammer which would be sufficiently heavy to forge the piece all the way into the center of the section, becomes so large that it is unwieldy. The press turns out a much larger production of large pieces than would a hammer suitable for the same work, and is less destructive on the dies and other equipment. The press is also used on special forging work, such as drawing, special punching and closed die forging, where it is almost impossible to use a hammer. Where a shape is intricate, rolling is more liable to tear the metal than hammering or pressing because, at the point where the roll is deeply cut, its surface velocity is much less than where the diameter is greater, and thus it tends to drag the metal through at different speeds.

Heating Furnaces

Heating furnaces are usually of the reverberatory type, burning soft coal or gas. The flame produced must be as reducing as possible in order to produce a small amount of scale. Much better control is obtained if the ash-pit is enclosed and forced draft is used to burn the fuel. In this way about half a ton of fuel will be required to heat a ton of steel from the atmospheric temperature to that necessary for mechanical work, with a loss of about 4 to 5 per cent. of the metal as scale. The gases must necessarily leave the furnace at a high temperature, and therefore it is not uncommon to have boilers situated over the heating furnace, in which steam is raised by means of the waste heat. With this economy the amount of fuel chargeable against heating the steel will be from 350 to 450 lb. per short ton of steel heated.

Regenerative Furnace.—If the heating furnaces are fired with

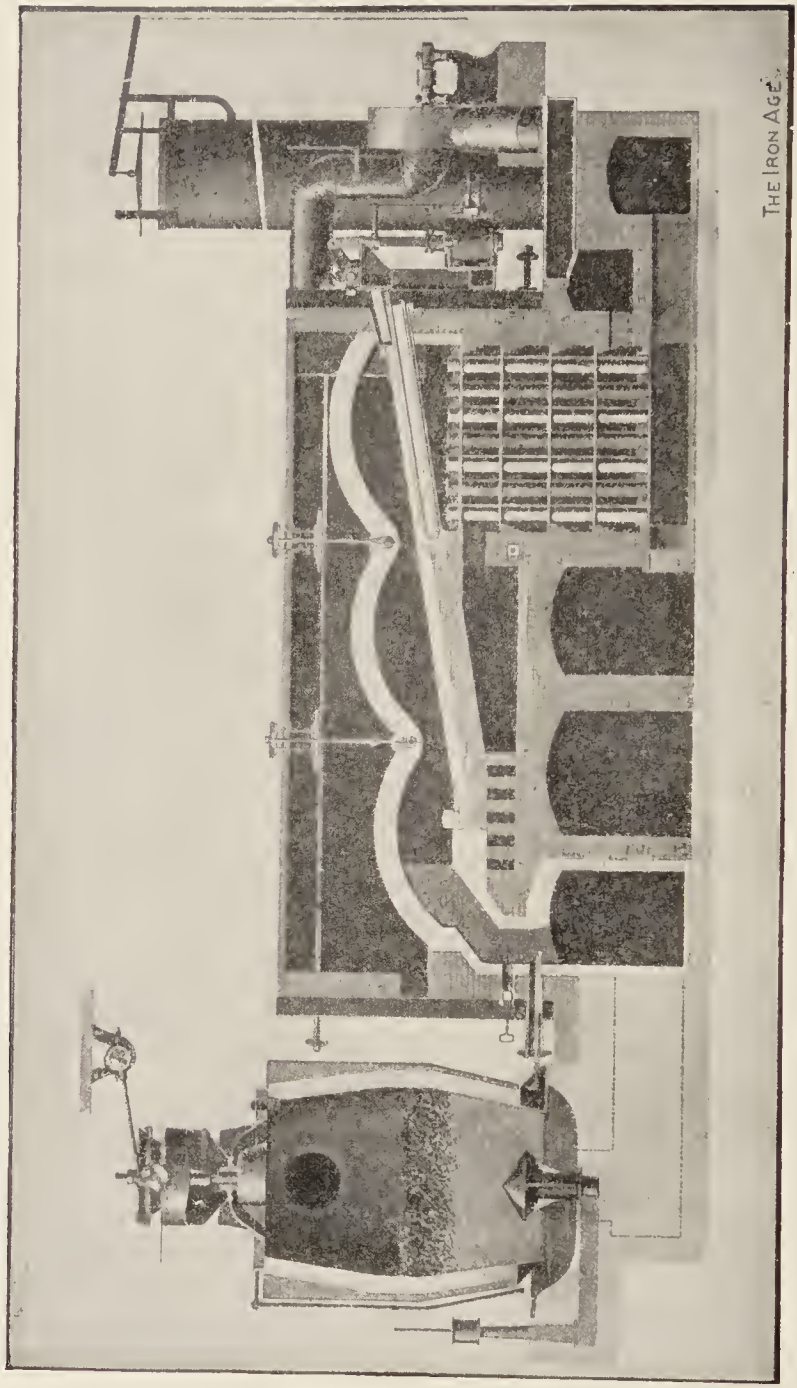


FIG. 178.—CONTINUOUS RECUPERATIVE HEATING FURNACE.

producer gas and the regenerative method is employed, we get a far better control of the temperature and of the reducing influence of the furnace gases. By this means a short ton of steel may be heated with from 150 to 200 lb. of fuel and with a loss of metal of from 1 to 5 per cent. by oxidation.

Continuous Furnaces.—Billets and other small pieces may be heated in furnaces whose action is continuous. Such a one as this is shown in section in Fig. 179. Along the hearth stretch two lines of pipe, which are kept cool by a stream of water inside. Upon the pipes is laid a long series of billets, which are gradually moved forward toward the end at which the gas and air enter. In this way the flame is always met by colder material and finally leaves the furnace at a relatively low temperature. As the gases pass out, they go through a series of pipes, *B, B,* around which circulates the air that is afterward led to the fire and used for combustion. As soon as the billet nearest the fire end is heated to the desired temperature, a new one is pushed in at the bottom, causing the hot billet to be shoved onto the inclined plane, whence it rolls out of the furnace to the point *A*, whence it is transferred to the rolling-mill. In this type of furnace a short ton of steel may be heated with from 120 to 145 lb. of fuel, with a loss in weight of less than 1 per cent. by oxidation.

Soaking-pits.—Ingots with molten interiors must be put in some form of the furnace in which they will stand upright until they have solidified throughout and are ready to roll, in order that the pipe may form in the upper portion. The type of furnace used for this is known as a soaking-pit and is shown in Fig. 180. The original intention of soaking-pits was to have the heat in the ingot itself bring the interior of the furnace and the mass of metal to the desired temperature; but this is not found practicable in the United States, and soaking-pits are usually heated by regenerated gas and air. The ingots must be kept in these soaking-pits long enough to be entirely solid in the interior, and for this purpose at least 55 minutes are required for 3-ton ingots when stripped and charged as soon as possible after teeming, and more for ones of larger size.

Furnace Bottoms.—Heating-furnace bottoms must be of some material not readily corroded by oxide of iron scale, and basic bottoms are very commonly employed with success. Heating-furnaces are also frequently supplied with a tap-hole, from which the slag, composed chiefly of oxide of iron, can be tapped at

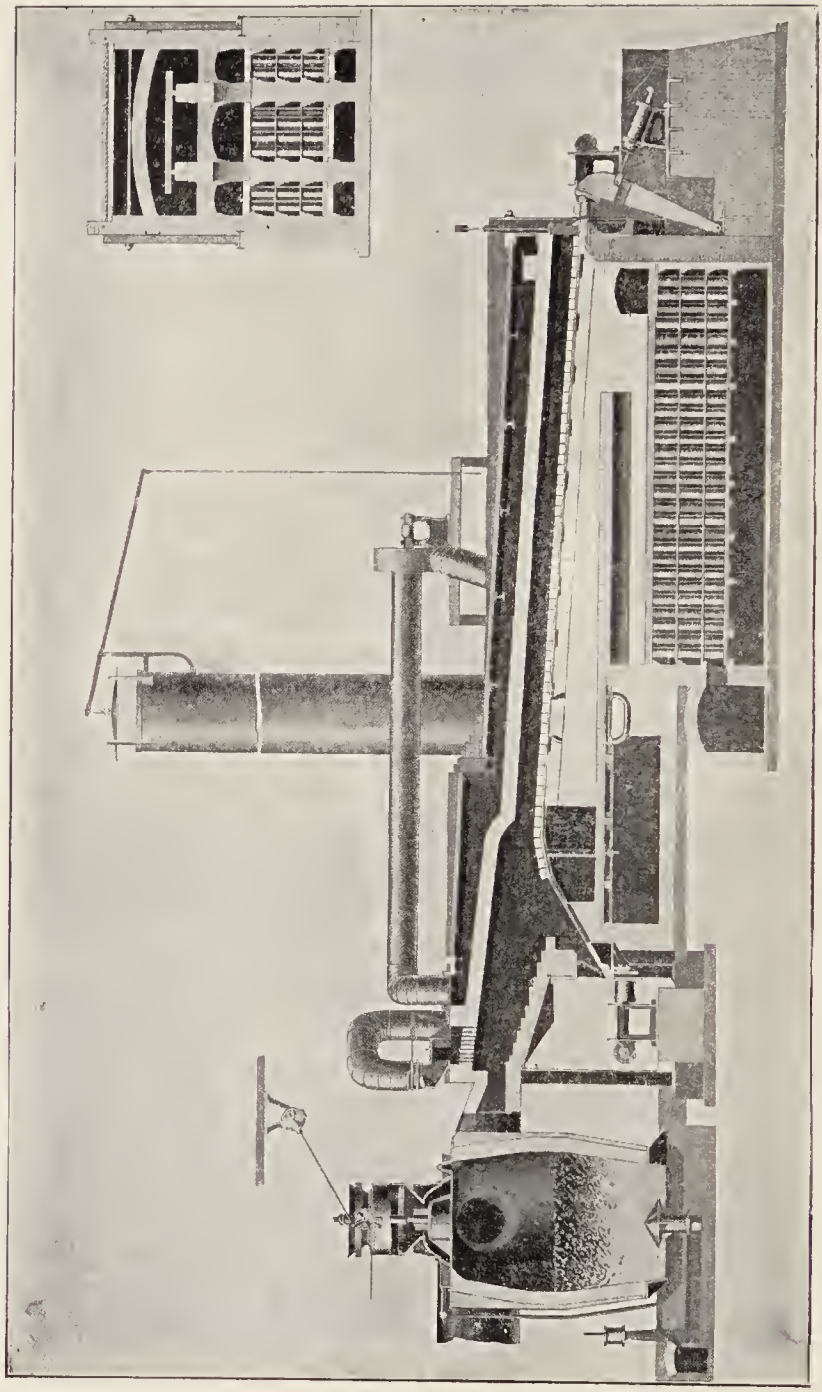


FIG. 179.—CONTINUOUS RECUPERATIVE BILLET HEATING FURNACE.
B B, pipes; C, ram for pushing in cold billets.

intervals. Soaking-pit bottoms are frequently covered with a layer of coke breeze to absorb the slag and prevent corrosion of the furnace bottom. This is shoveled out when an opportunity is afforded, and new breeze substituted, or is knocked out through a hole in the bottom, for which see Fig. 180.

Heating Practice.—In heating steel for rolling, the lower the temperature the better will be the quality of the product. On the other hand, if the metal is to undergo many passes before it receives another heat, it must be correspondingly hot, in order

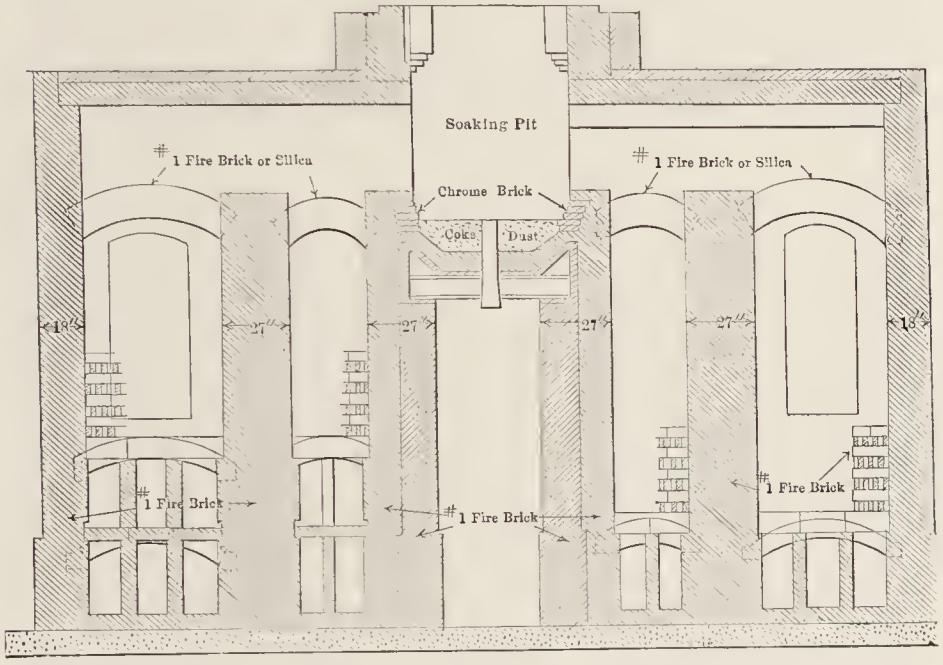


FIG. 180.—BRICKWORK OF REGENERATIVE GAS SOAKING-PIT.

that the finishing temperature may be high enough to avoid excessive power for reduction. There is no doubt that rolling temperatures at the present time are higher than they should be, for the metal when finished should be only just above the critical temperature of the steel. Until within recent years no suitable pyrometers for measuring the temperature have been available, and the temperature for drawing the material is judged by eye, so that no figures can be given. There can be no doubt that more careful attention to this point will result in less waste in rolling (on account of the production of cracked or second-class material because of too hot steel at the starting) and in the production of a higher quality of steel.

It must be remembered, however, that the steel must be hot enough to cause it to weld together wherever it has become cracked. This is especially to be observed in low-carbon steel whose welding, as well as its melting-point, is higher than that of high-carbon steel. The casting temperature and the absence of ingotism which the author has discussed elsewhere is probably

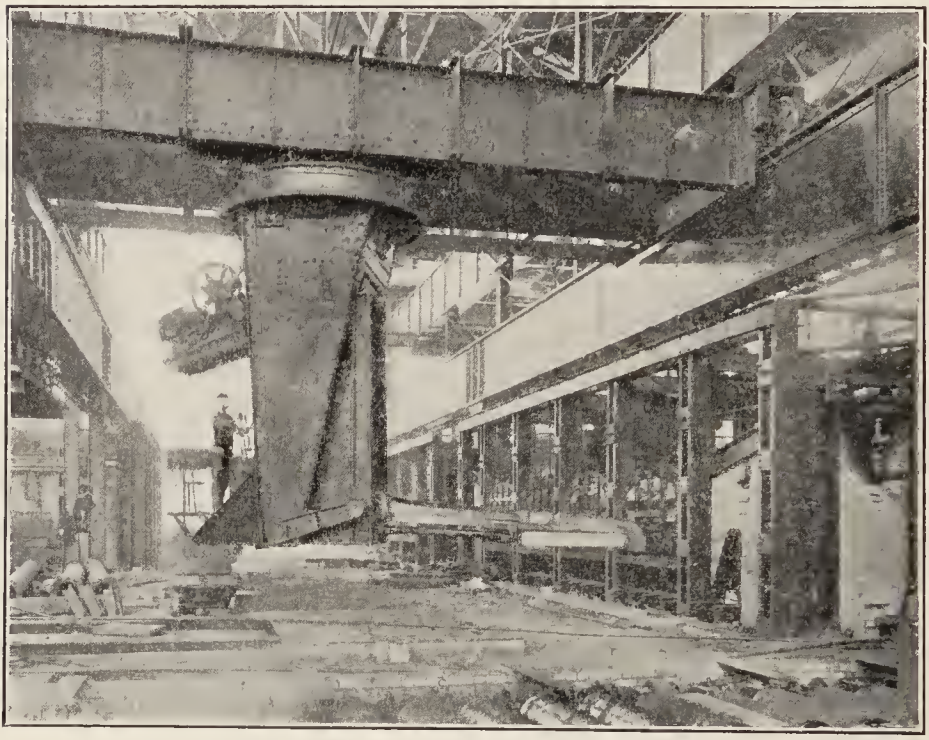


FIG. 181.—CHARGING A SLAB INTO A HEATING FURNACE.

more important than any other factor in preventing cracking during rolling, as properly made steel can stand without injury a high temperature which would be very harmful otherwise. High-carbon steel is very delicate to roll especially when the silicon also is high.

IX

IRON AND STEEL FOUNDING

FOUNDING is a mechanical art, and consists in pouring melted metal into a mold of any desired size and form, which the metal assumes and retains when cold. The mold is made of some kind of sand, with rare exceptions to be mentioned hereafter. The art is a very complex one, added to which it is now passing through an important transition period in which science is very

Sweeping up a mold.

FIG. 185.—VIEW IN AN IRON FOUNDRY.

rapidly taking the place of rule of thumb. It is impossible to treat the subject adequately in a single chapter, but several books are now available, to which foundrymen, metallurgists and chemists are referred, and which are also recommended to all engineers, to whom a knowledge of the art is of prime importance.

The Making of Molds

There are various kinds of sand molds made for foundry work, but the three principal kinds are *loam molds, dry-sand molds,* and *green-sand molds.*

Loam Molding.—In molding with loam, sand is usually built up into the required shape by hand, aided by machines. Fig. 205

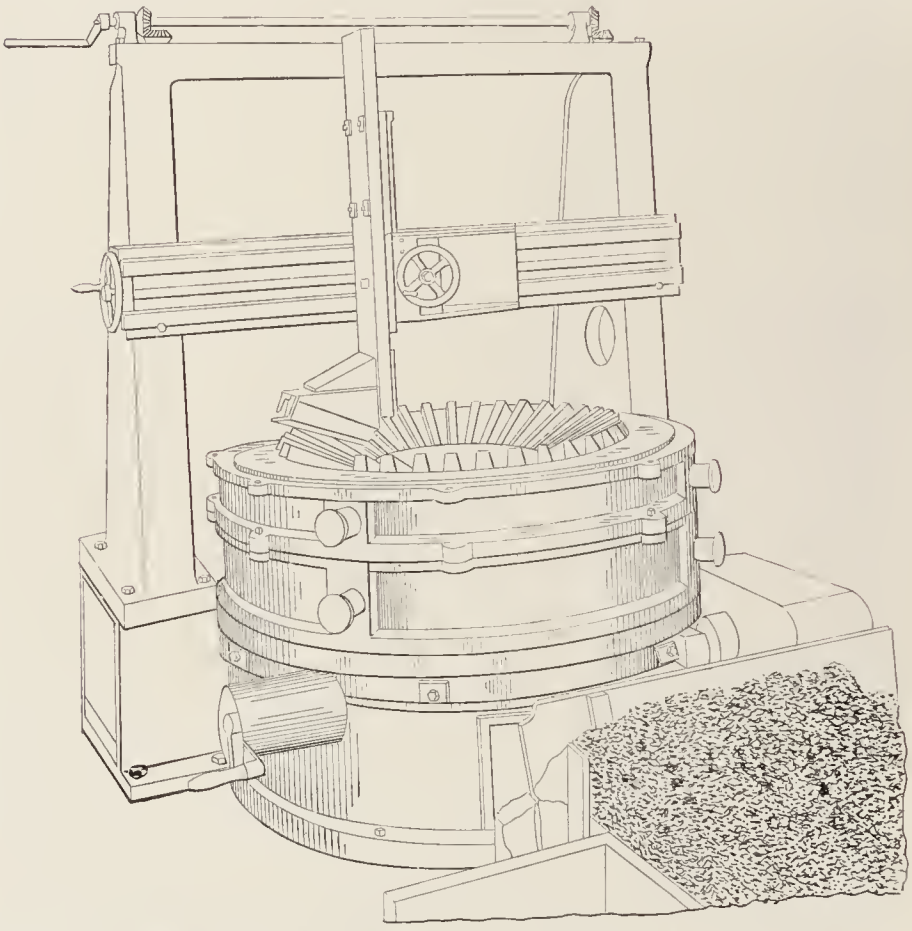


FIG. 186.—MACHINE FOR FORMING THE TEETH OF A BEVEL-GEAR.

shows the molding of a gear in which the parts are built up of brick and sand and then "swept" into the proper shape by means of the wooden sweeps. Large wheels and gears are often swept up in this way, the teeth being formed subsequently by means of a small pattern that is moved around as the molder progresses, or by means of a machine, as shown in Fig. 186. In the case of a gear, the arms are usually formed by placing within the swept-up

mold forms of sand known as "cores," as shown in Fig. 187. Loam molding is common in iron foundries, but almost never used for steel castings.

Pattern-molding.—To only a limited class of work is loam-molding applicable, and the commonest manner of making a mold is to press or ram sand around a pattern, which is subsequently removed, leaving the desired cavity. Usually the pattern is en-

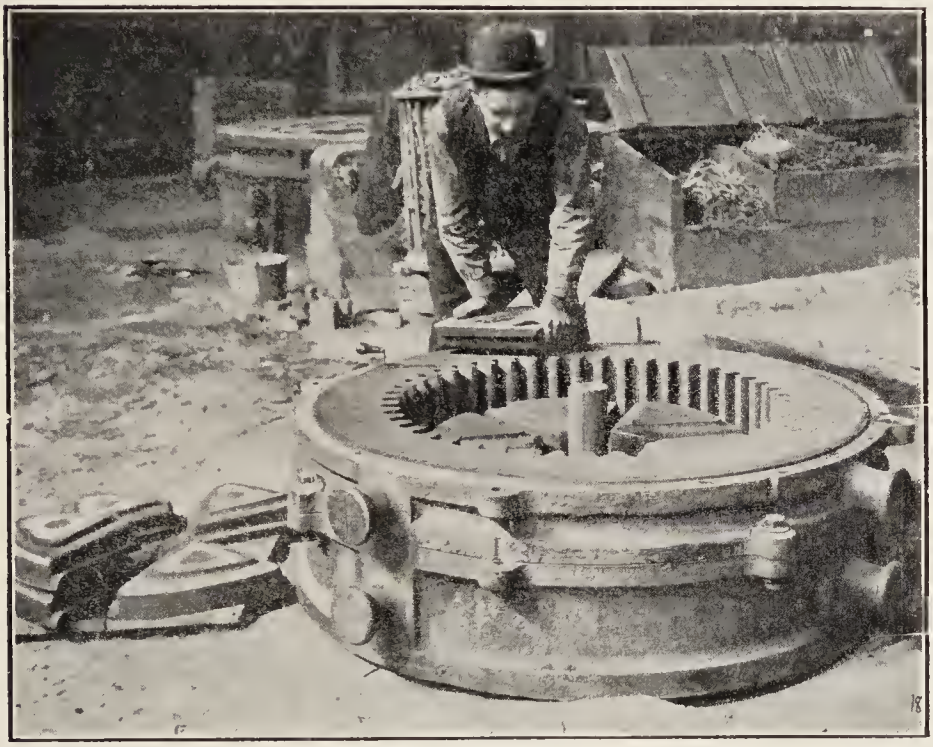


FIG. 187.—PLACING CORES IN A MOLD.

closed by a "flask" much larger than itself, between which and the pattern the damp sand is rammed. The pattern (sometimes) is split into halves, one half being in the lower part, or "drag," of the flask, and the other half being in the upper part, or "cope."[1] The cope is now taken off and turned upside down, after which a lifting-screw is inserted into each half of the pattern in turn, by means of which it is drawn from the sand; and when a "grate" is cut through the cope, the flask is again fastened together, and a receptacle is formed of the shape of the pattern into which the metal may be poured.

[1] The old English word "cope," meaning a covering for the head, which has now largely been replaced by the name "cap."

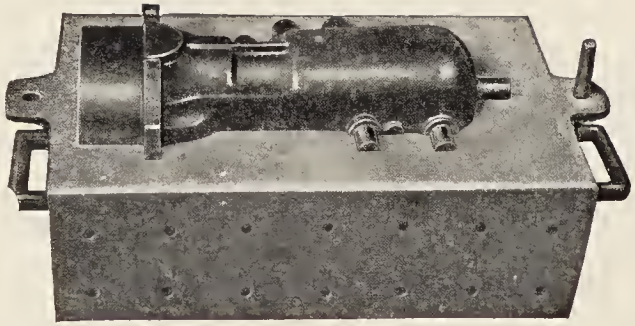


FIG. 188.—MAKING THE MOLD.
Pattern in the sand of lower section of flask.

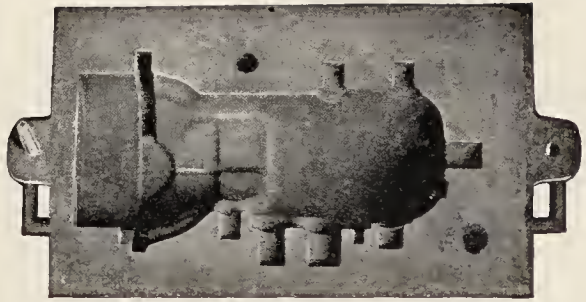


FIG. 189.—MAKING THE MOLD.
Pattern removed from sand showing molded impression.

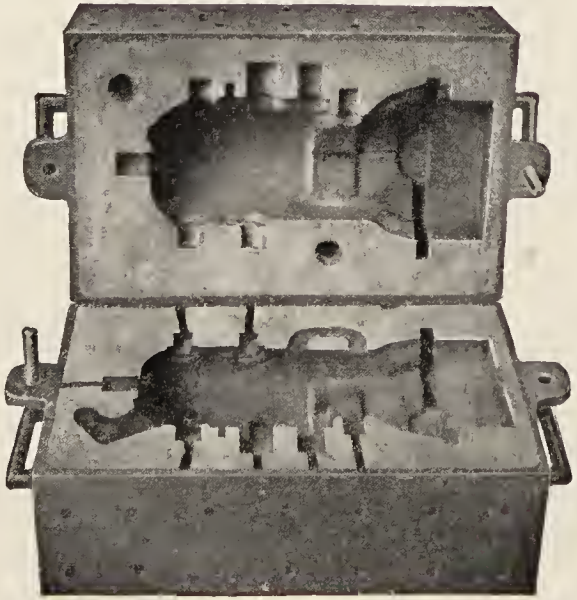


FIG. 190.—MAKING THE MOLD.
Upper and lower sections of flask molded and ready to receive cores.

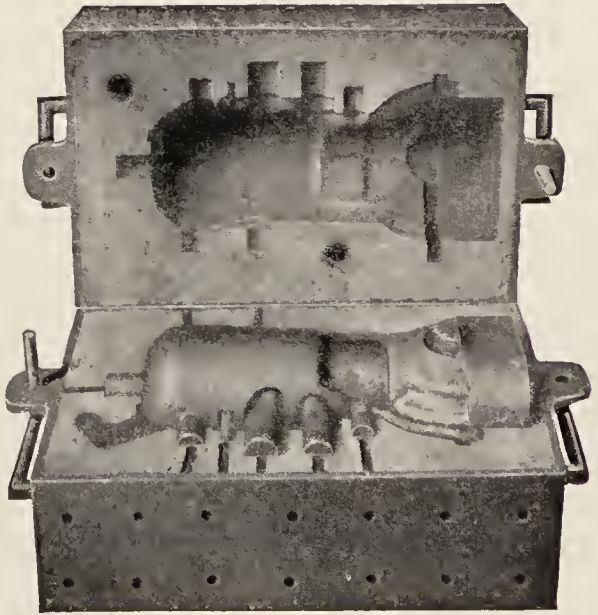


FIG. 191.—COMPLETING THE MOLD.
Cores in place.

The art does not consist of these simple operations alone, however, for in drawing the pattern from the sand, even though the lifting-screw be lightly tapped with a hammer is four horizontal directions to loosen the pattern, the slightest tremble of the molder's hand, or of the crane used for lifting, may cause the sand to be broken in places, and the chief skill of the molder as well as a large share of his time is employed in repairing the damage thus produced. Furthermore, the mold may be "washed," that is,

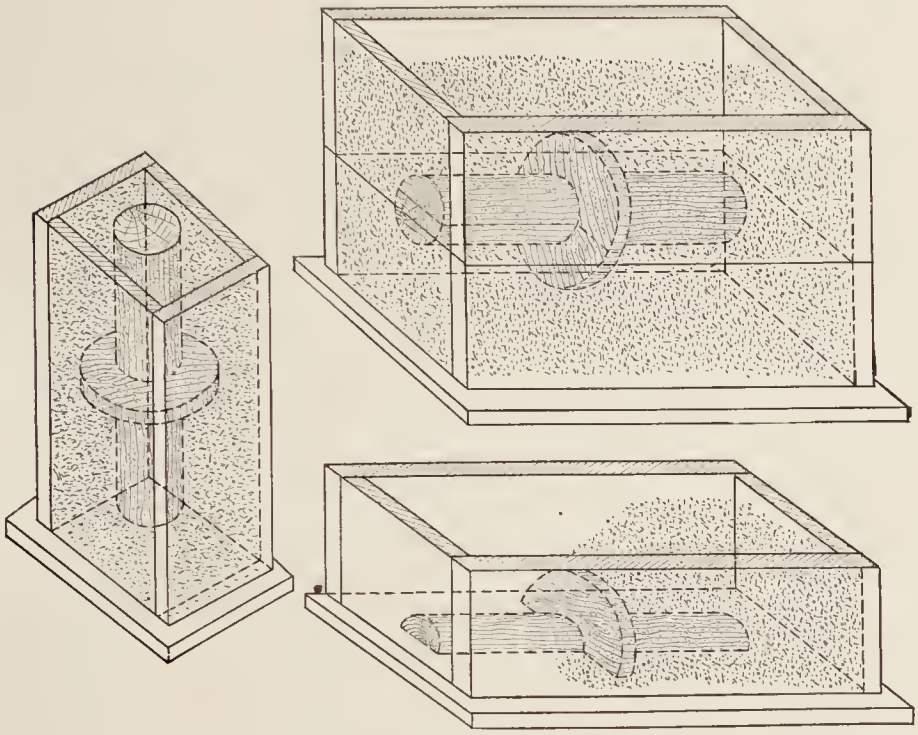


FIG. 192.—PATTERN IN SAND.

painted inside; the proper cores must be put in place; parts of the sand liable to drop off must be nailed in place with thin, large-headed wire nails thrust in with the thumb; before the pattern is taken from the sand the cope must be "vented," that is, made porous, by jamming a wire into it many times and pulling it out again, so that the air and gases will escape when the metal is poured in; and so on.

Furthermore, it may readily be imagined that parts of the pattern as shown in Fig. 192 might be of such a shape, with flanges on the bottom, or something of that kind, that they could not be drawn without breaking the sand. In the case of such a design

the pattern and flask must be split into three or more parts,[1] or else a core must be put in to make an offset. It will be evident to every engineer that he will have to pay more for making a casting so designed.

Ramming.—In pattern molding, it is essential that the pressure of the sand around the pattern shall be nearly uniform in all places; because (1) when the metal is poured into the mold, it

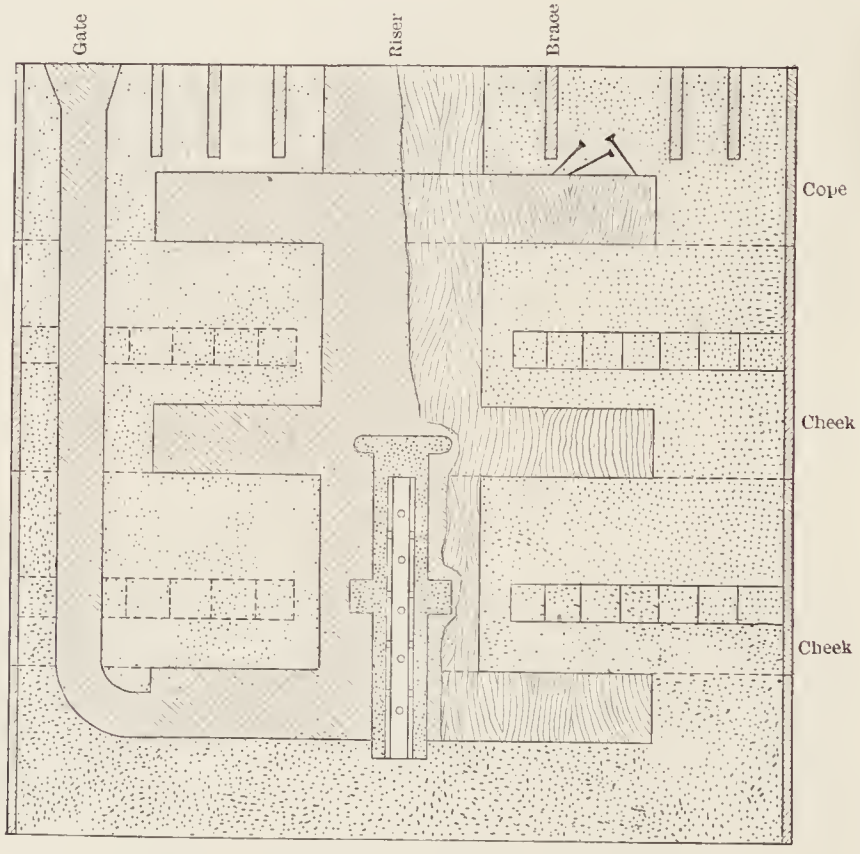


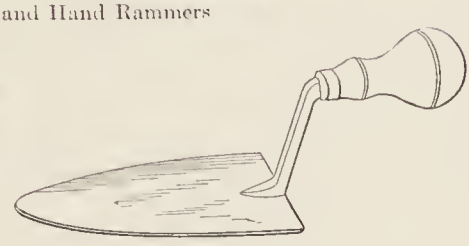
FIG. 193.—SECTION OF FLASK AND PATTERN.

drives out the air already there by forcing it through the interstices between the particles of sand, and if the sand is too hard in any place, the pressure of air collected there is liable to form a depression, or "scab," in the casting; and because (2), if the sand is too loose in any place, the pressure of the metal upon it is liable to "swell" it outward and thus cause an enlargement of the casting at that point. To obtain uniformity it is necessary

[1] The bottom and top parts being still known as the "drag" and "cope," respectively, while the intermediate parts are known as "cheeks."

Floor and Hand Rammers

Finishing Trowel

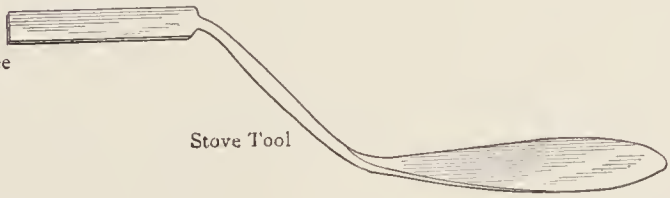


Finishing Trowel

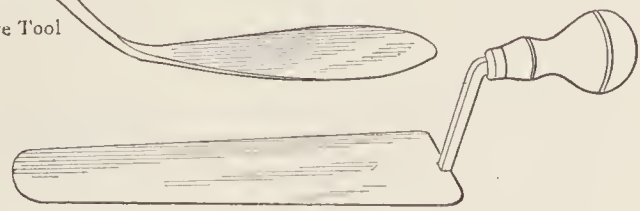
Yankee

Lifter

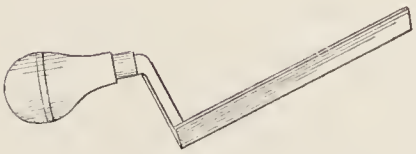
Bench Lifter



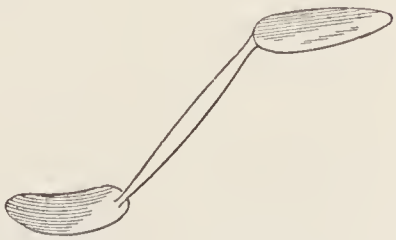
Stove Tool



Finishing Trowel



Square Trowel



Slick and Spoon

FIG. 194.

that the sand be packed around the pattern, and not the pattern pushed into the sand. This packing is accomplished by the hands for the sand immediately adjacent to the pattern, and by rammers for the layers further distant. In the case of bench molding hand rammers are used, and for making larger molds on the floor long iron rammers are employed. The molder's skill is shown in applying the proper amount of power in ramming each different kind or part of pattern.

Dry-sand Molds.—After ramming up the mold, drawing the pattern and applying the "wash," the mold may be used green (when it is called a "green-sand mold"), or it may be put in the ovens and dried (when it is called a "dry-sand mold"). The drying has the effect of driving off the moisture and leaving a firm, hard mass, semi-baked into a sort of brick. Sand for these molds should have slightly more clay than for green-sand molds; otherwise, instead of baking into a hard mass, they would be liable to crumble with the heat. The temperature of drying-ovens should be about 350° to 400° F. (170° to 200° C.), and they are heated by coke, coal, gas or oil. If the temperature is too high, the mold will be burned, that is, it will crumble under the fingers after drying; if not hot enough, the mold will not be baked hard. The length of time in the oven will depend upon the size of the mold, and will vary from an hour or so to a day or so. During the drying the molds are liable to shrink somewhat, due to the action of the clay in binding together.

Green-sand Molds.—Green sand requires less clay than dry-sand, because it has a certain coherence due to its dampness. Many natural sands are found suitable for both the green-sand mold and the dry-sand mold, or they can be made up as desired by mixing a good clay with a sand rich in silica. Green-sand molds must not be rammed as hard as dry sand, so the moisture may more readily evaporate.

Washes.—For iron castings the common wash is graphite dust, which is made up into a paint with water and applied with a brush or dauber to the inside of a dry-sand mold before it goes to the oven. In the case of a green-sand mold, pulverized coal is dusted onto the surface through a piece of cloth, and then spread uniformly with the "slicker." In the case of a dry-sand steel casting, the wash is composed of pulverized silica rock, running from 98 to 99 per cent. silica, which is made up into a thick paint with water, thickened with molasses, and applied to the inside of

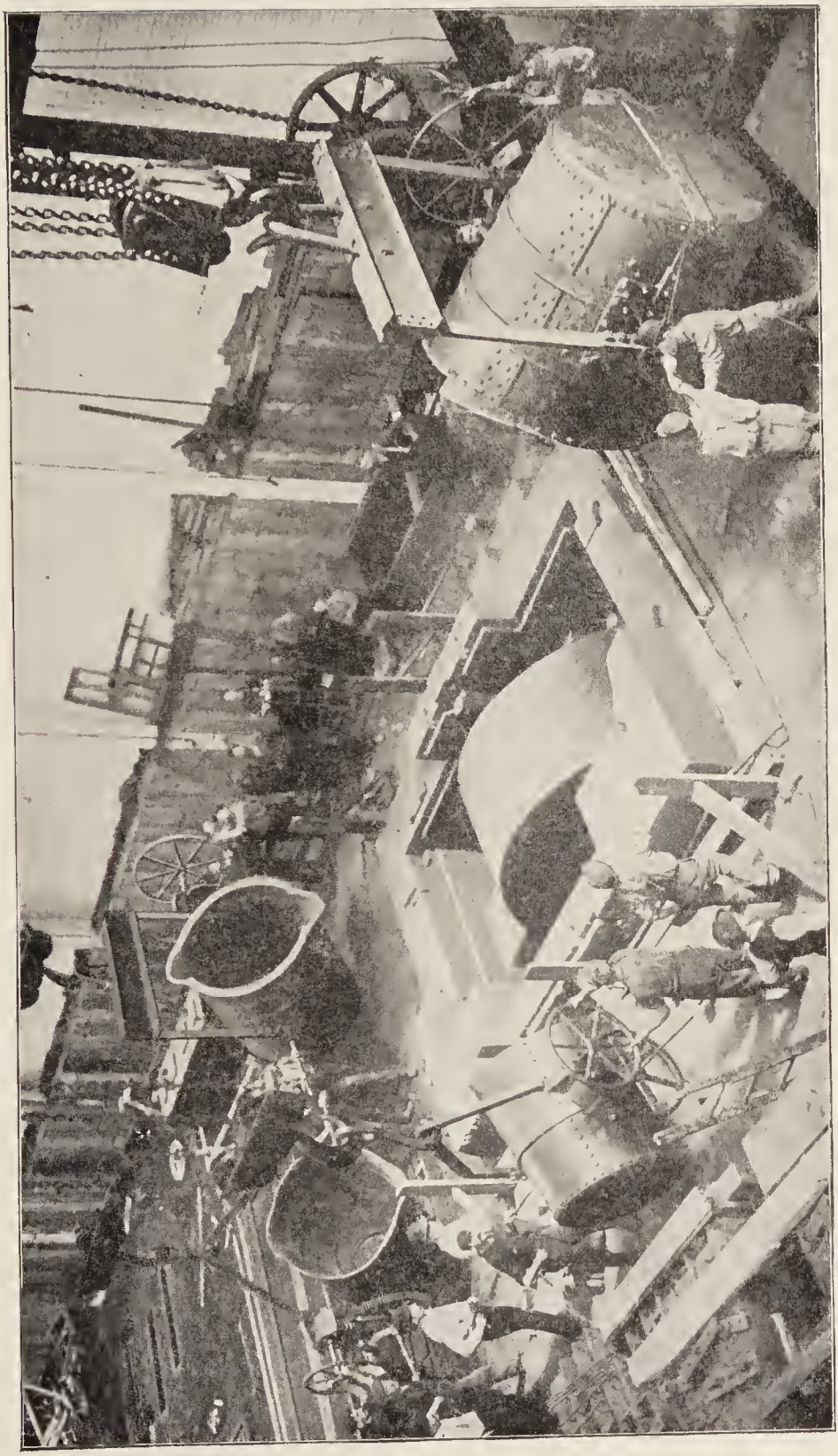


FIG. 195.

the mold with a brush or dauber before the mold is dried. Green-sand molds for steel castings cannot ordinarily be washed. Graphite washes cannot be used for steel molds, because the hot metal attacks the graphite and becomes rough upon its surface.

The functions of washes are: (1) To make a very smooth face on the sand, so that the surface of the casting shall be smooth (this they accomplish by the very fine size of their particles); (2) to give a surface that shall resist the melting and chemical action of hot metal, so the castings may be easily cleaned of sand.

Skin-dried Molds.—The inside surface of green-sand molds is occasionally dried by painting or spraying it with some inflammable liquid, such as gasolene, and then applying a match. This is more common in steel-foundry than in iron-foundry practice, and produces a little better surface to the casting. Herbert B. Atha patented a mold wash for green-sand steel castings which would enable them to be skin dried.[1] The formula for this wash was devised by me with the aid of Parker C. McIlhiney. It consists of ordinary gasolene in which is dissolved as much rosin as it will take up without warming. The rosin increases the specific gravity of the gasolene so that it forms a paint with the silica wash, which would otherwise sink to the bottom and not adhere to the brush. After the wash is applied, it is touched with a match, the burning resulting in giving a dry skin to the mold and leaving it coated with the silica. The rosin does not completely burn off, but binds the sand together and gives a tough skin, so that the sand is not so liable to drop when the cope is turned over to place it upon the drag.

Dry- versus Green-sand Molds: For Iron Castings.—Dry-sand molds are often cheaper to make and require less molding skill, because (1) the sand does not have to be tempered so carefully, that is, brought to the proper condition of dampness, since the moisture is eventually to be driven off by the drying. In green-sand molds, if the sand is too wet, it is liable to "cut" (be eroded by the stream of metal) and get dirt into the casting, and also to be impervious to the gases. (2) The sand requires less care in ramming, because, whether too hard or too soft, the expansion and contraction in drying will adjust its firmness and porosity. (3) Furthermore, the dry sand is stronger, which is an advantage, when the sand is liable to be under pressure from the metal, or to have the metal fall upon it from a height. (4) Dry-sand castings

[1] U. S. Letters Patent No. 686,189.

are also more liable to be sound, because there is less gas in the pores of the sand.

The disadvantages of dry-sand castings are: (1) The mold is liable to shrink during drying and therefore be less true to the pattern; (2) the castings are more liable to "check" (that is, crack in cooling), because the mold is firmer and so does not give way so easily to the crushing action when the casting contracts; (3) molds exposed to the direct action of the flame during

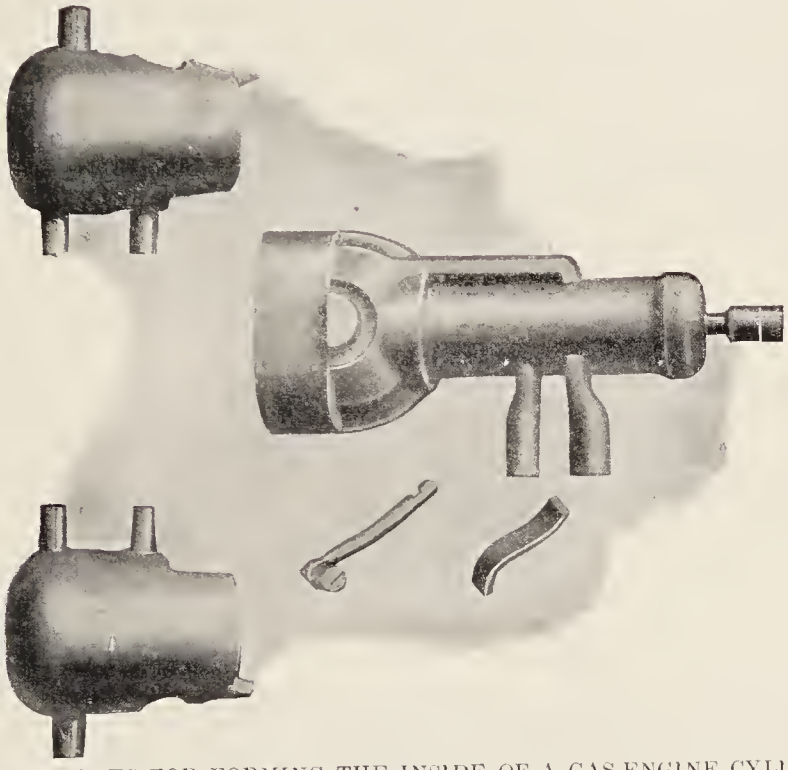


FIG. 196.—CORES FOR FORMING THE INSIDE OF A GAS-ENGINE CYLINDER CASTING.

drying, or heated too hot, are liable to be burnt and therefore rendered useless, causing a loss; (4) in handling, the molds are liable to be damaged; and, furthermore, it is more costly to repair a dry mold than a damp one, because the adjacent sand must first be damped, the damage repaired, and then a flame applied to dry the wound; (5) it takes longer to complete an order. The actual cost of heat is not very great, and usually is less of an item than the extra labor of handling for drying.

For Steel Castings.—Dry-sand steel castings have a surface

much superior to those made in green sand.[1] They are also stronger and more liable to be sound. Soundness is much more difficult to obtain in steel castings than in iron castings. Green-sand molds, however, have the great advantage of allowing their

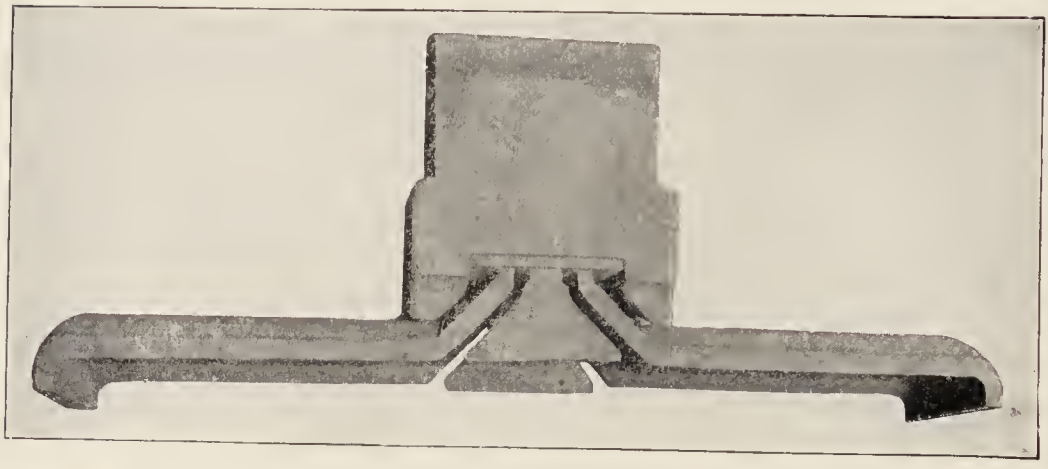


FIG. 197.—CORE.

sand to crush more easily when between two parts of the casting that are being drawn together by the shrinking of the metal. This is doubly advantageous in steel work, because steel shrinks twice as much as cast iron and is therefore more liable to checking. Special means may be employed for making the sand easily collapsible after the metal is poured, such as mixing with

FIG. 198.

it an inflammable substance like flour, chopped hay, hay-rope, sawdust, coke, etc., which burns away after the hot metal is poured in.

Cores.—The function of cores has already been referred to: they are set inside the mold proper to assist in forming the metal.

[1] One reason that dry-sand steel castings have a better surface is because they can be washed. In practice, however, the drying and washing is often improperly performed; therefore green-sand castings often have the better surface.

The commonest use for them is to extend through a casting in some place to make a hole, as, for instance, the inside of a cylinder, the bore of a pulley, etc. In this position they are subjected to great crushing strain when the metal shrinks, and therefore the

FIG. 199.

bond which keeps the sand together, consisting of linseed-oil, or flour paste, a patented core compound, etc., must be of such a nature that when subjected to the heat of the liquid metal it will burn away and allow the sand to disintegrate, which both pre-

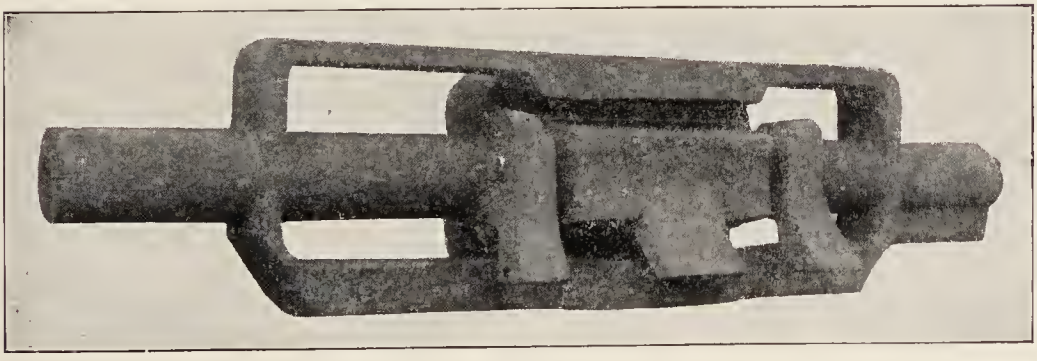


FIG. 200.

vents it bursting the shrinking casting and permits of its being more easily cleaned out. Cores are often built up around an iron pipe riddled with holes, so that the gases formed may readily escape through this "vent." In the case of large cores, the pipe

is frequently wound with hay-rope, or some similar material that will burn away and make the sand more collapsible. Some cores have coke breeze or cinder in the center to make them light as well as porous.

Cores are supported sometimes by being set in the drag, sometimes by being hung in the cope (see Fig. 202); but it is more common to have a hollow adjunct to the mold, known as a "core-print"

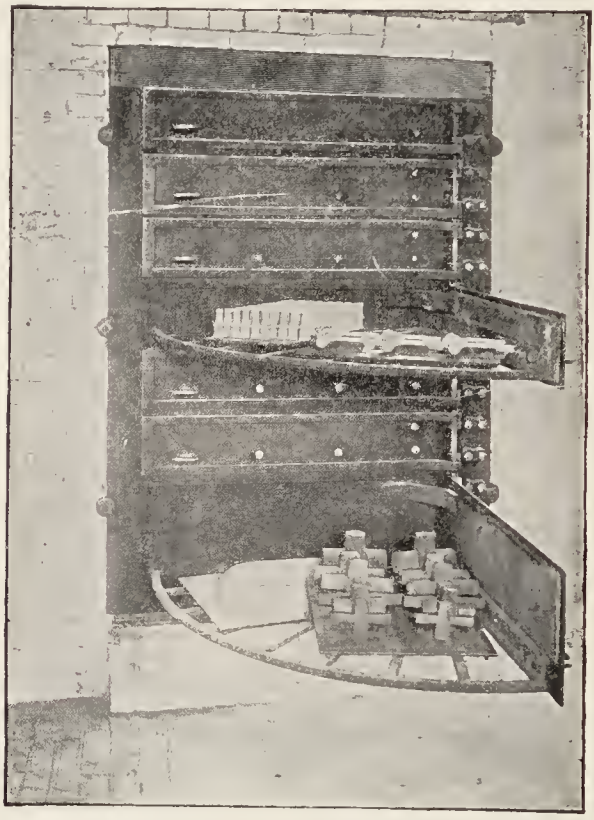


FIG. 201.—OVEN FOR DRYING SMALL CORES.

into which an extension of the core fits (see Fig. 190). Sometimes both ends of the core are so supported, and sometimes only one end is thus supported, while the other end rests upon a metal chaplet that is absorbed in the casting when the metal is poured. Cores are often dried, lest their gases make the casting unsound or cause it to blow, that is, boil with the rapid escape of gas through the metal.

Chill Molds.—It is often desired to chill certain parts of a mold, or cool them more rapidly than the remainder, in order

either to make a thick part of a casting solidify as soon, or sooner, than the thinner portions, or else to produce white cast

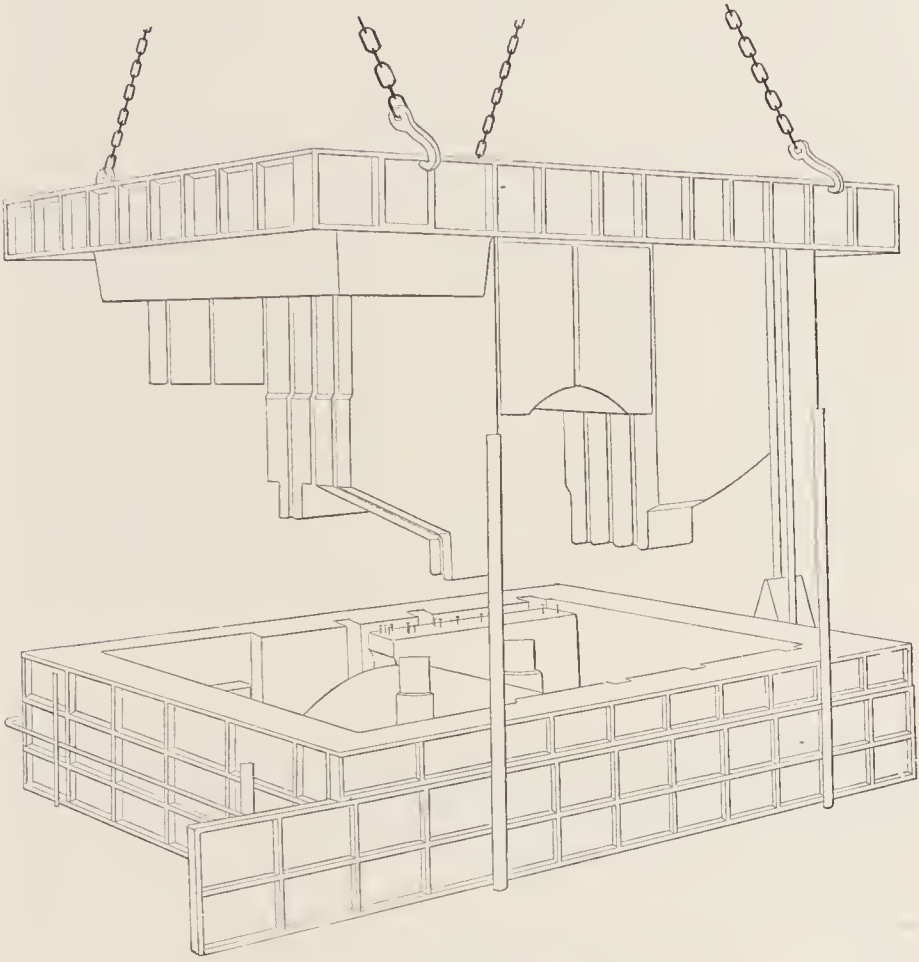


FIG. 202.—CORES HUNG FROM THE COPE.

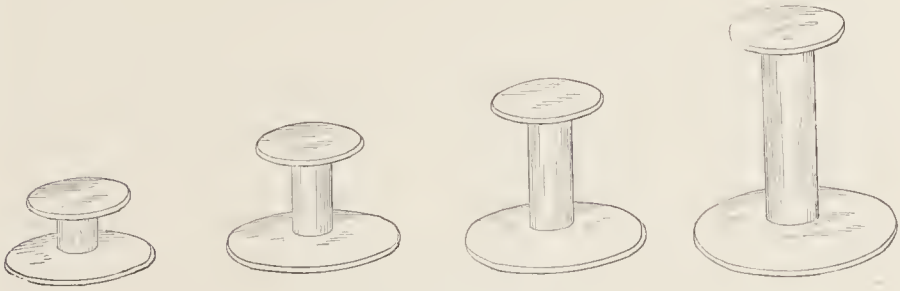


FIG. 203.—CHAPLETS.

iron at that point. The former may be desirable in the case of either an iron or steel casting, becaused the shrinkage cavity

FIG. 204.—POSITION OF MACHINE WHEN PRESSING THE DRAG.

FIG. 205.—POSITION OF MACHINE WHEN PRESSING THE COPE.

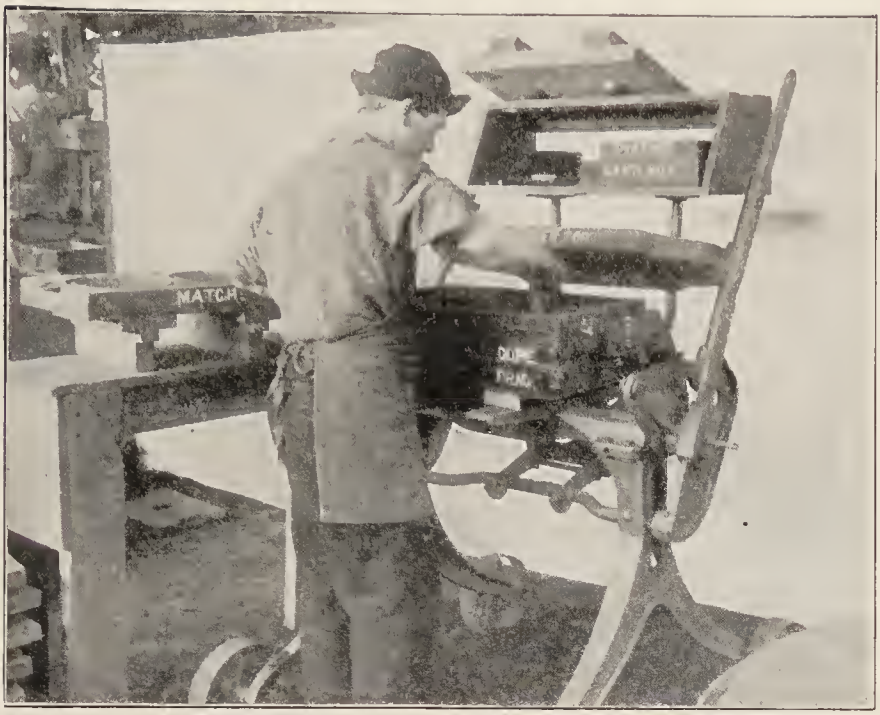


FIG. 206.—CUTTING SPRUE WITH TUBULAR SPRUE CUTTER.

FIG. 207.—RAPPING THE PATTERN BEFORE SEPARATING THE MOLD.

occurs in the last portion to freeze, and therefore hastening local freezing may be necessary to bring the pipe into the riser or feeder. The latter applies only in iron-casting work in which it is desired to make the outside of a casting very hard. The chilling is usually accomplished by embedding pieces of metal in the sand, against the face of which the casting is poured. This metal is oiled, blackened or "washed," so that it does not stick to the casting.

Permanent Molds.—A great deal of expense in foundry work is due to the fact that a sand mold must be made anew for every

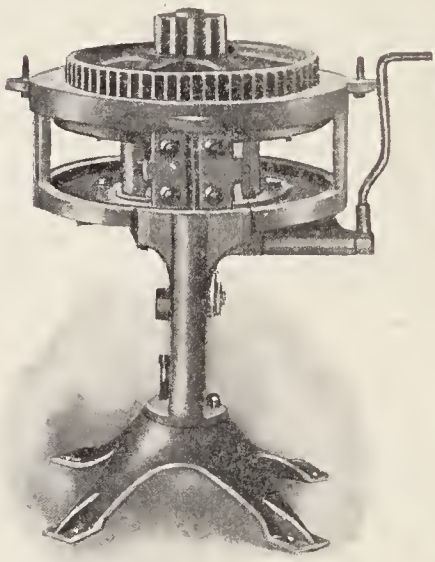


FIG. 208.—STRIPPING PLATE MOLDING MACHINE.

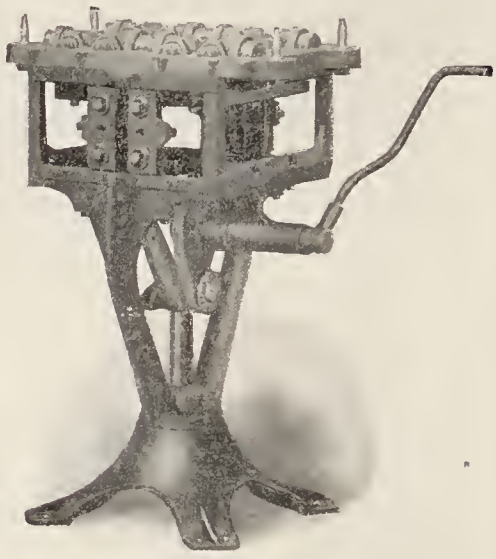


FIG. 209.—STRIPPING PLATE MOLDING MACHINE.

casting, and the subject of permanent molds has occupied the attention of foundrymen for a great many years without the problem being completely solved. When a casting is knocked out of the mold, the sand is usually knocked out also and its form destroyed. In the rare case of a smooth cylinder, or something of that kind, the casting may be withdrawn without damage except to the face of the sand, and this can sometimes be repaired and swept up anew without re-forming the entire mold. Again, molds for railroad car wheels, which have a metal "chill" all the way round the tread and flange, in order that the cast iron may be white at that point to withstand the grinding action on the rails, have a certain amount of permanency. Finally, molds

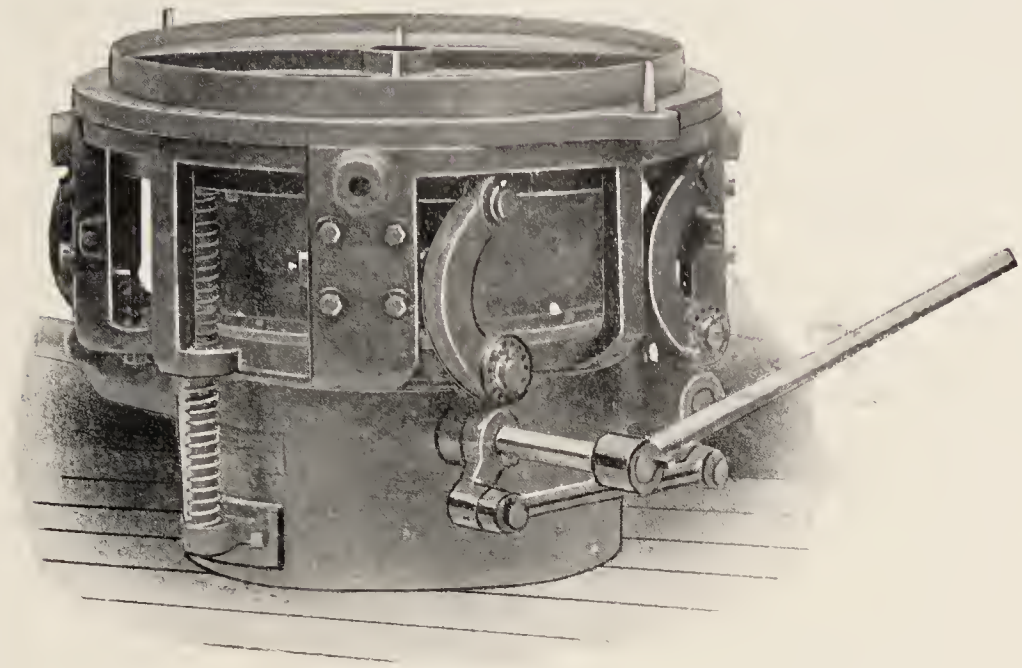


FIG. 210.

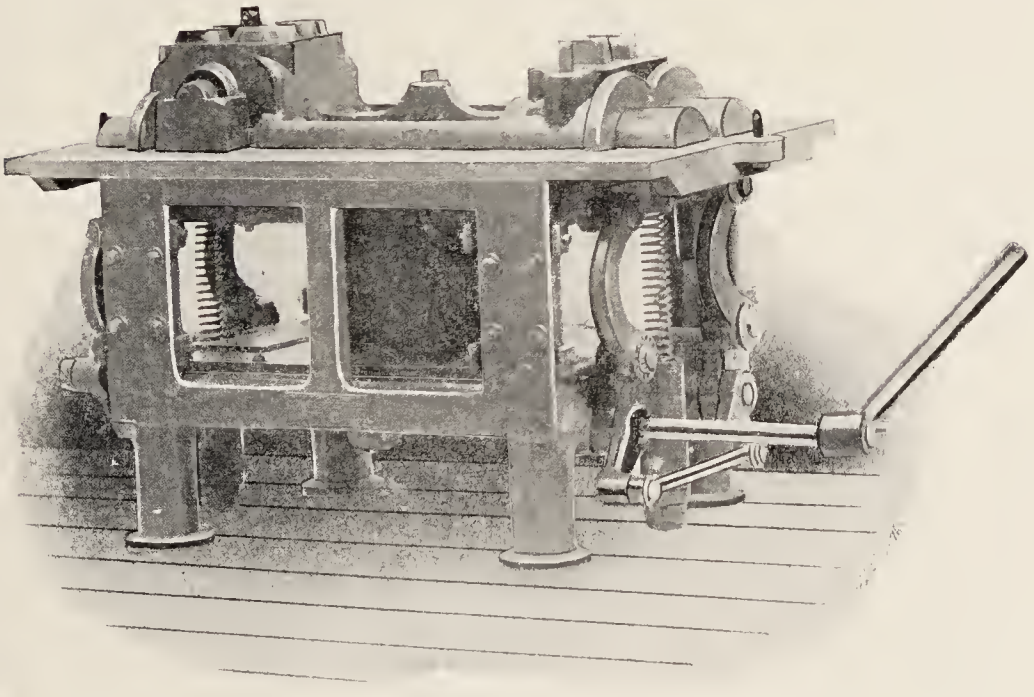


FIG. 211.

carved out of carbon which has been preheated to a very high temperature are said to withstand the action of the melted metal and to last for a large number of castings.

E. A. Custer has developed a method of casting gray iron in cast iron molds, and such objects as pipe, ornamental castings, etc., are being successfully made in this manner. The molds last a very long time and the principle of the process involves arrangements whereby the molds can be opened as soon as the iron has chilled, the cores removed, and the casting taken out of the iron mold to cool more slowly in the air, with the result that the metal, if it has the proper chemical composition, is not chilled but deposits graphite so that the castings may be readily threaded or machined. For certain classes of work, this method would appear to have a great field of usefulness, promoting economy, rapidity and a certain degree of independence of labor conditions. It is obvious that the only castings that can be made in this way are ones of which a large number are required so that it would pay to make up the necessary molds. The results are also interesting from a scientific standpoint in that they confirm the observation referred to elsewhere, that graphite separates from cast iron after solidification, as indicated by the circumstance that the iron will be gray if removed from the mold immediately or shortly after solidification, but the carbon will be in the combined condition and the iron will be white if it is allowed to cool in contact with metal. (See Reference No. 97).

Gating of Patterns.—The gate of a mold is the place into which the liquid metal is poured (see Fig. 193) while the sprue extends from the gate to the casting proper. The placing of gate and sprue is goverened by certain principles whose best application can only be learned generally by experience. Referring especially to Fig. 193, we see for example that if the metal were poured into the riser of the casting it would drop upon the core and knock this to pieces. Even if this core were absent, the metal in dropping from such a height onto the sand bottom of the mold, would wash sand from it and make a defective casting because of the cutting of the mold at this point as well as the probable inclusion of some of the sand in the solid metal. Furthermore, the metal would spatter on the sides of the mold and frozen drops might accumulate which would afterward form a "cold shut" on the side of the casting. It is rarely good practice to pour a

casting through a riser, and whenever the metal is poured from a height, it is well to insert a refractory fire brick upon which the stream shall strike. Steel castings are almost always poured from the bottom in a manner in general similar to Fig. 193, and this method is often followed in case of gray iron as well. The general principles of gating may be very briefly summarized as follows:

(1) The metal must be forced into the mold fast enough to prevent its chilling at any point, so that sprue and gates must be amply large; in the case of a thin casting, for example, this may

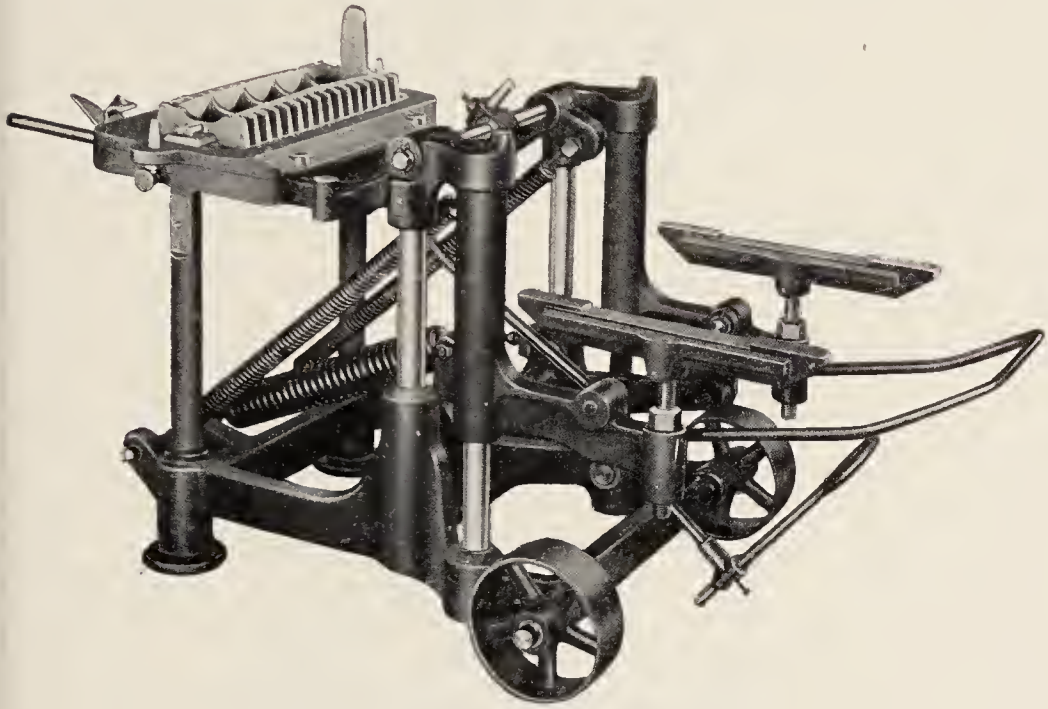


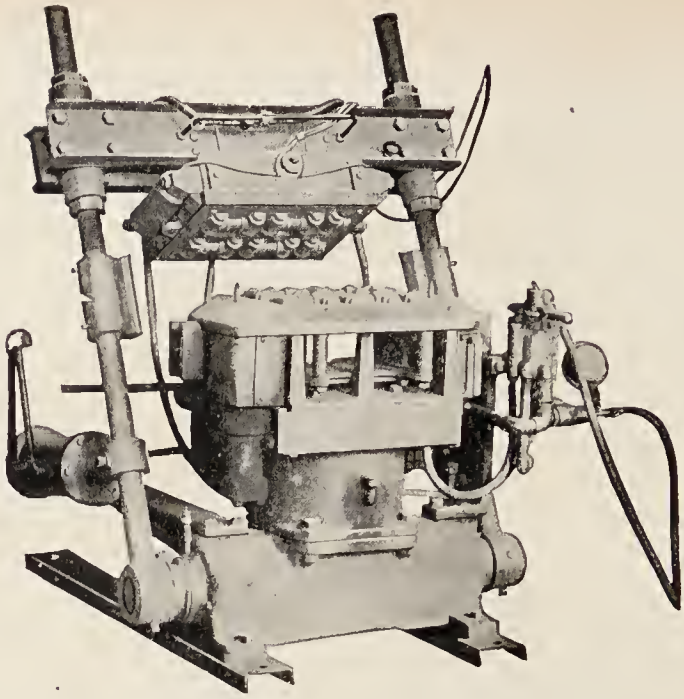
FIG. 212.—ROCK-OVER MOLDING MACHINE.

necessitate having the metal enter at a number of different points at the side of the mold.

(2) On the other hand, unnecessary amplitude is to be avoided since the sprues have only the value of scrap.

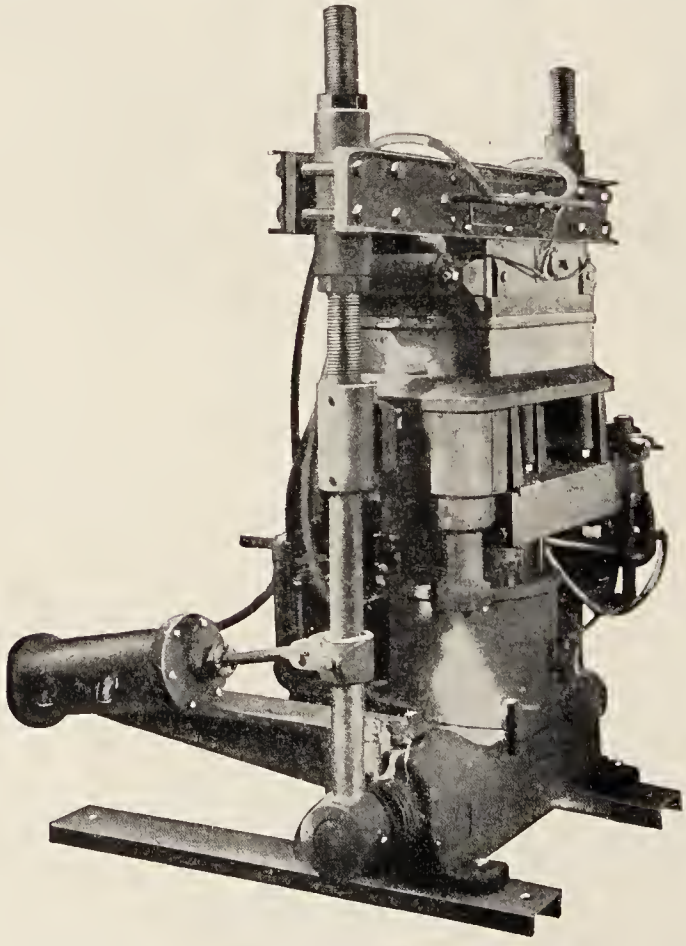
(3) The stream of metal must not wash against the sand in such a way as to cut it. We may exemplify this by an example in steel castings where the stream of metal is usually brought in at the bottom and with a certain tangential direction so that it shall rise in the mold with a rotary motion.

(4) The metal must not have too far to run. In large or long



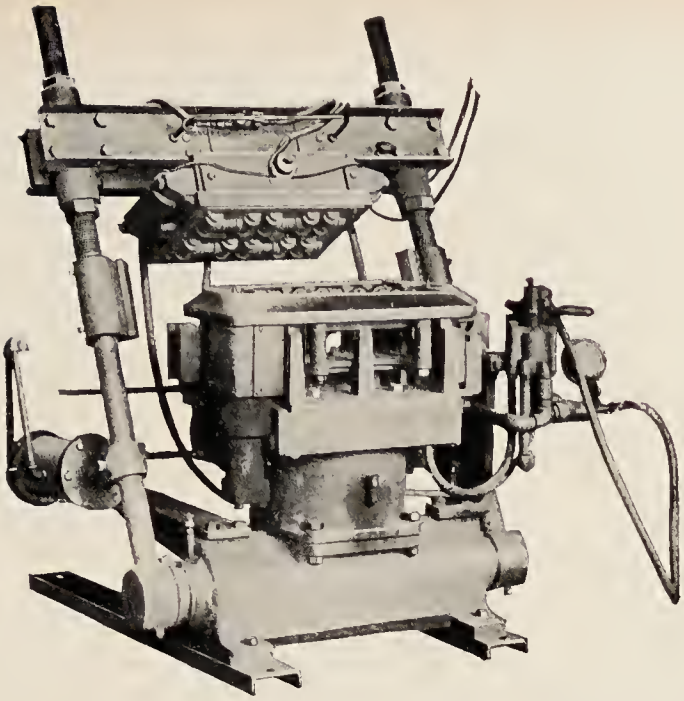
Upper head swung back to receive flask.
Cope patterns on lower head.

Drag patterns on upper head.
Yoke swung by power.

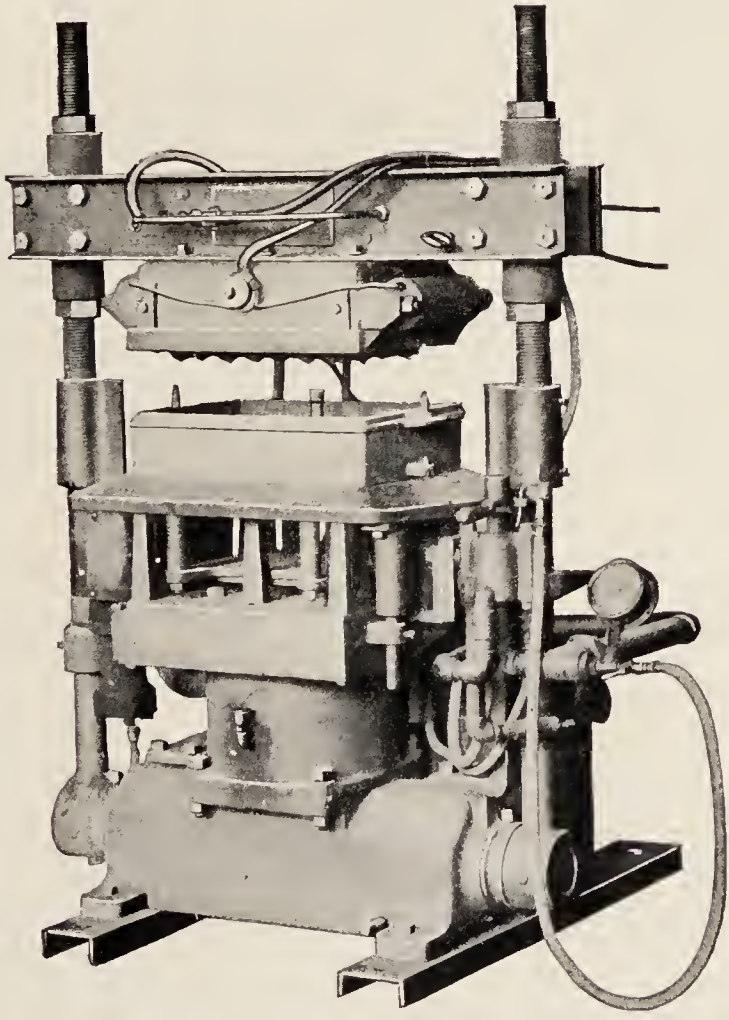


Sand frame on flask.

FIGS. 213 AND 214.—VIBRATOR MOLDING MACHINE.



Mold removed, flask frame raised, showing method of drawing cope patterns.



Mold lowered away, drawing drag patterns. Drag patterns may be returned with absolute accuracy.

FIGS. 215 AND 216.—VIBRATOR MOLDING MACHINE.

castings this may necessitate gating at several different points:

(5) As far as possible we must arrange to pour into a reservoir and to have the rate of pouring such that this reservoir shall be kept as nearly full as possible in order that any slag or dirt accidentally getting in at this point, may tend to float to the top of the metal and not be carried into the casting proper.

(6) The point at which the metal enters is the hottest part of the casting, and this must be borne in mind when considering

FIG. 217.—VIBRATOR.

the question of feeding, to avoid shrinkage cavities. Sometimes it is desirable to chill this location in order to artificially oppose these conditions.

(7) In placing a gate we must remember that as the metal shrinks, it will draw the sprue towards the casting. The spuer being the hottest part, there may be a tendency for this contraction to tear the metal in two and especially to tear the sprue off at the point where it joins the casting proper, thus making an unsightly defect.

Gated Patterns.—Where the castings are very small, a large number of them will be made into one pattern, fastened onto a

common "gate" through which they are poured, which produces very great economy in molding. (See Fig. 219).

Molding Machines.—At the present time various types of molding machines are being extensively introduced into foundries, in order to save some of the labor or skill required in molding, or both. The simplest form of machine is the "squeezer," which may be described by reference to Fig. 204. The correct amount of sand is poured into the flask and by means of a long lever the "presser board" is forced down on top of this sand,

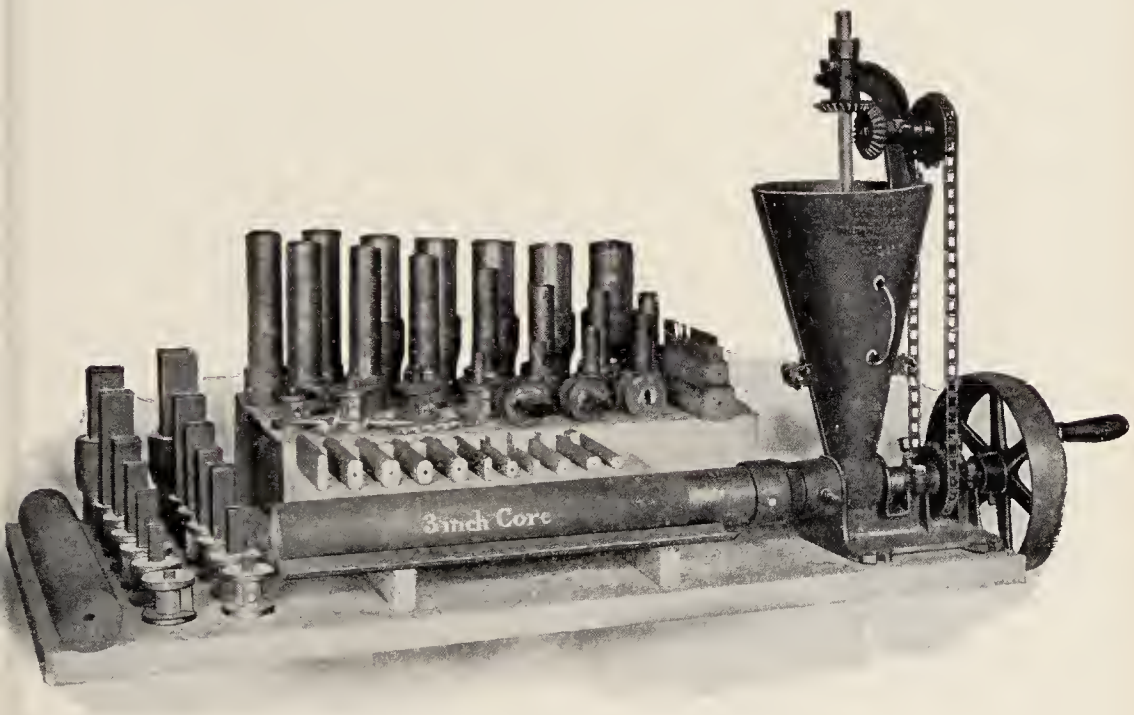


FIG. 218.—CORE MACHINE AND CORES.

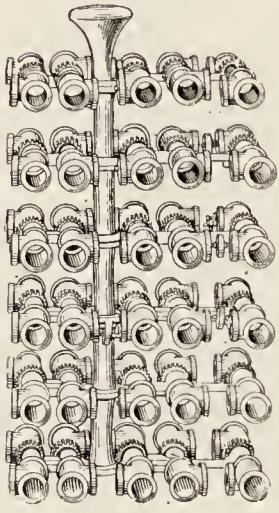
squeezing it around the pattern and producing a half mold. In taking the flask off the pattern by hand, damage may be done the sand, and the molder's skill is still required to repair it.

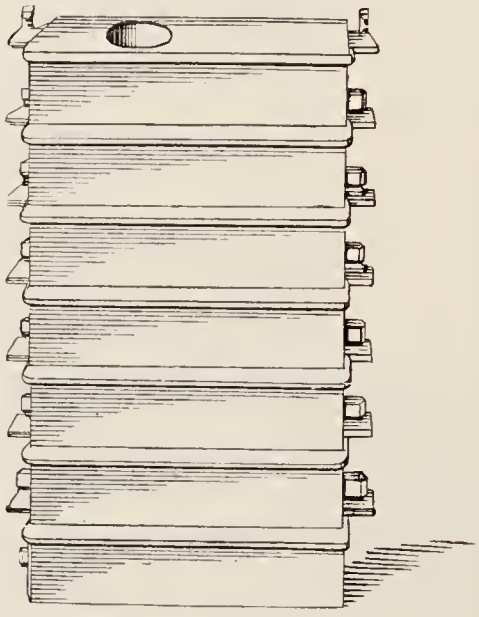
The stripping-plate machine obviates part of this difficulty, however. In this type the half pattern may be pushed up or down through a close-fitting hole in a plate known as the "stripping-plate" (see Fig. 208). After the sand has been rammed around the pattern, a lever draws the pattern down through the stripping-plate. As this drawing is mathematically exact, no damage results to the sand and no repairs to the mold are

necessary, so that unskilled laborers may be employed for the work.

A still further extension in the line of machines is the "vibrator," whereby the pattern is vibrated an extremely small amount, some 5000 to 30,000 times per minute, during the drawing of the pattern. No stripping-plate is necessary to separate it from the sand, since the vibrator frees it perfectly and without damage.

In all these molding machines the operation may be conducted either by means of levers, or by a mechanism operated by hy-





FIGS. 219 AND 220.—MULTIPLE MOLD AND CASTING.

draulic or pneumatic power, and several hundred patterns may be made per day by one man who is very little, if any, more skilled than a common laborer; and machines are made in which castings weighing from a couple of ounces to several hundred pounds may be molded with great economy.

Core Machines.—There are also on the market several machines for making cores, an example of which is shown in Fig. 218.

Multiple Molds.—During the past few years a new type of molding, known as "multiple molding," has come into use, in which several flasks are placed in a pile and poured through a common gate of sprue, as shown in Fig. 219. This type of molding saves mold costs, flasks, sand, floor space, and the weight of metal wasted in sprues, and many difficulties have been over-

come, so that the castings are now made accurately to size and good in all respects.

Contraction.—A bar of cast iron 12 in. long will contract about 0.125 in. during solidification and cooling (i.e., it will be about 11 7/8 in. long when cold. See page 328 for further details), while a bar of steel will contract about twice as much. In both cases the contraction in sectional dimensions will not be as great as in length.

Design of Patterns

The foregoing description will show what a great financial advantage it is to a purchaser if he designs castings that can be easily molded, and if he can order a large number of castings of exactly the same design. It is certain that a hundred castings of one design can be made with very much greater cheapness than the same number all of different designs, and of this economy the purchaser obtains his full share, because the foundry is glad to encourage such a customer and to make concessions in order to do his work. I cannot recommend too strongly to engineers the practice of making the castings in all similar machines interchangeable, both for the sake of economy and of avoiding some delay and expense in replacement after a breakdown. The correct design of castings is furthermore one of the most important branches of engineering work, since the number of castings used is almost one-half of the total number of pieces used in engineering work, while their weight is equal to about one-sixth of the weight of all the iron and steel employed. The following general hints are therefore offered to assist in this design; but each casting is a study in itself, in order that the various desiderata referred to may be obtained.

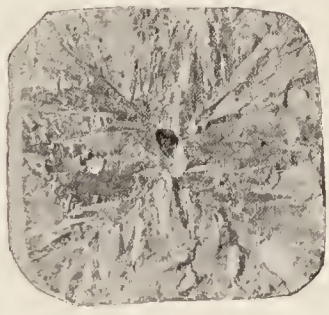


FIG. 221.

To Avoid Checks.—The commonest error in engineering designs of castings is to make the corners too sharp, which makes them very liable to check, because of the crystalline character of iron and steel. This is the more important, because the greatest leverage comes at the corners, which therefore should be made as

strong as possible. Metals are crystalline substances and the crystals grow during solidification. As solidification usually extends from the surface inward, the crystals grow in a direction perpendicular to the cooling surfaces. As shown in Fig. 221, this results in a line extending inward from all corners, marking the junction of many crystals. As the junction lines of crystals are not as strong as the crystals themselves, this makes a line of weakness on corners, which is the more marked the sharper the corner is. In case a casting is to be machined, it is much better to put a large fillet in all the corners, even if the rounded metal must be cut away later, as greater strength is obtained in this way.

The checking of castings comes from the strain produced by the contraction of the metal tending to crush the sand. This is the more intense the greater the distance between the two crushing parts, because they must approach each other by an amount exactly proportional to the length of metal between them. It is therefore wise, wherever possible, to avoid long lengths of metal connecting two parts which project into the sand.

Unequal cooling strains will also cause a check. This may be illustrated by a pulley with thick arms and a thin face. The face will solidify first and therefore yield very little to the subsequent contraction of the arms. Moreover, the face, being cooler, will then be stronger and the tendency will be for the arms to tear themselves in two. To avoid this it is common practice to chill the arms either by setting metallic pieces in the mold, or by means of a "water gate." A water gate is a loose column of coke molded into the sand of the cope, down which water may be poured.

To Avoid Shrinkage Cavities.—The formation of a "pipe" or shrinkage cavity has already been explained. Such a defect in a casting would be intolerable, and is commonly avoided by having a reservoir of metal situated above the casting proper and large enough to keep it supplied with molten metal until it has completely solidified. This reservoir is known as the "riser," or "header" (sometimes merely "head"), or "feeder." The riser is included as a part of the mold when it is made, but is cut off the finished casting and used over again as scrap. Sometimes castings are so designed by engineers that a heavy section of metal must be molded underneath a thinner section. As the thinner section will solidify first, it cannot "feed" this lower,

heavy section; and therefore a special form of riser is required, or else the heavier section must be artificially cooled. Iron castings usually do not form shrinkage cavities, but steel castings must be fed carefully to all parts.

Cupola Melting of Iron for Castings

Iron for castings is melted either in the cupola or the air furnace,[1] although "direct castings," i.e., castings made from the metal just as it comes out of the blast furnace, are used in many cases, and especially for cast-iron ingot molds at steel-works. For this practice it is necessary to employ men with sufficient expertness to be able to judge by eye the character and the analysis of the liquid iron as it flows from the furnace, because the metal may vary greatly and without warning from one cast to another. Sometimes, also, metal mixers are used, similar to those at steel-works.

In the cupola (see Fig. 222), a layer of iron rests on top of a bed of white-hot solid fuel. Air is blown aganist this fuel; the oxygen unites with carbon, and the resulting hot gases, as they pass upward, melt the iron. The layer of iron is not deep; it should therefore all be melted in less than 5 or 10 minutes. During this interval the fuel is being consumed also. Now a new layer of fuel rests on the bed to replace what has been burned, and a new layer of iron on top of that. By correct proportioning of the alternate layers of fuel and iron, the new layer of iron will occupy exactly the position of its predecessor, this location being the "melting zone" of the furnace.

Cupola Zones.—The cupola should be so operated that certain well-defined zones of action will be maintained, in order that rapid, hot and economical melting will result and that loss by oxidation be small. If proper conditions prevail all of these desiderata may be obtained together, while, if otherwise, wasteful methods may be accompanied by slow, irregular melting and "dull iron," i.e., iron not sufficiently hot.

Crucible Zone.—The crucible extends from the bottom of the cupola to the level of the tuyeres. The object of this part is to form a place in which the iron and slag may collect after they have melted and trickled down. If the tap-hole is kept open all

[1] The air furnace is used in gray cast iron, chilled iron and malleable cast iron foundries and will be discussed in Chapter XIII.

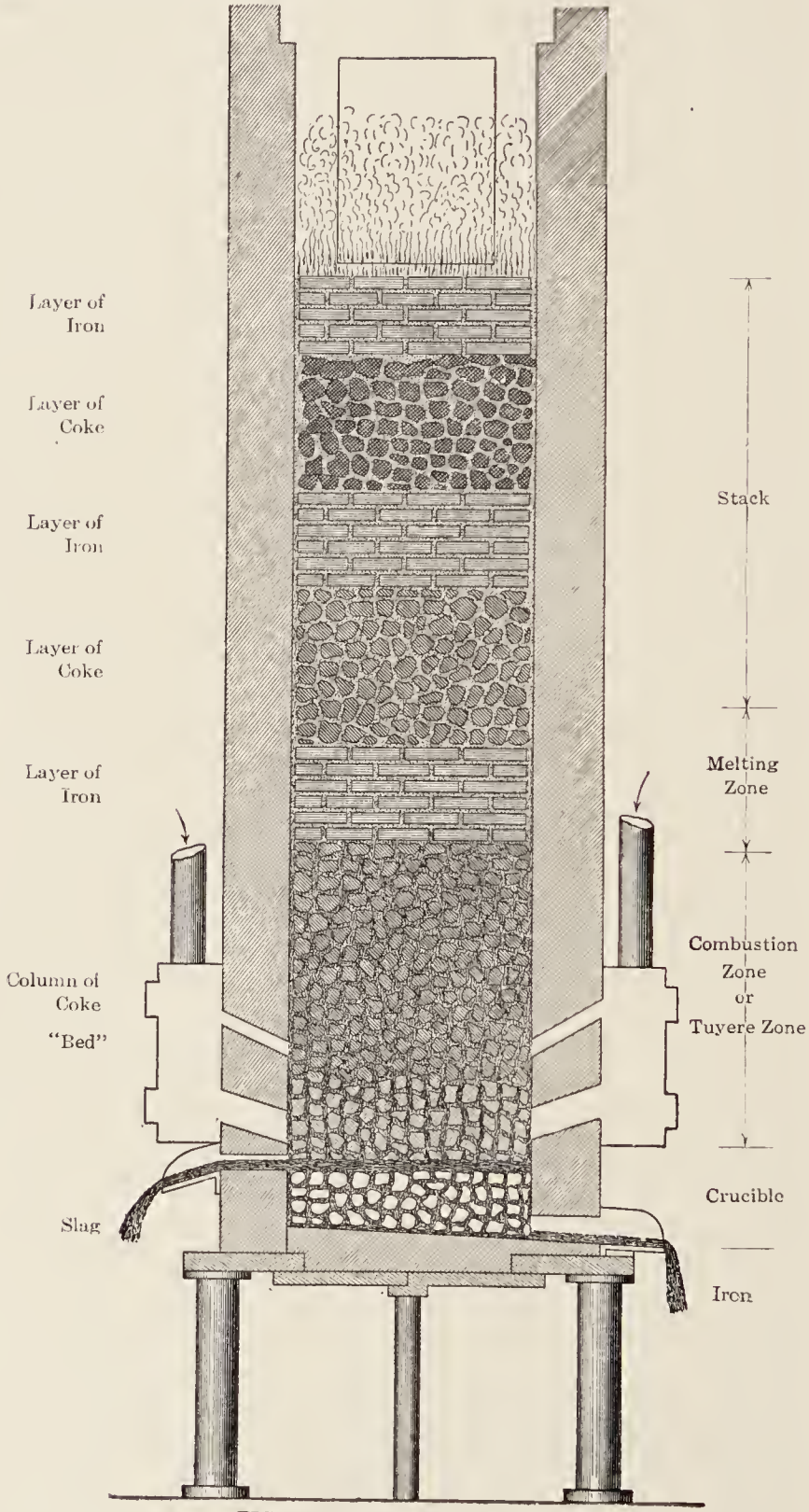


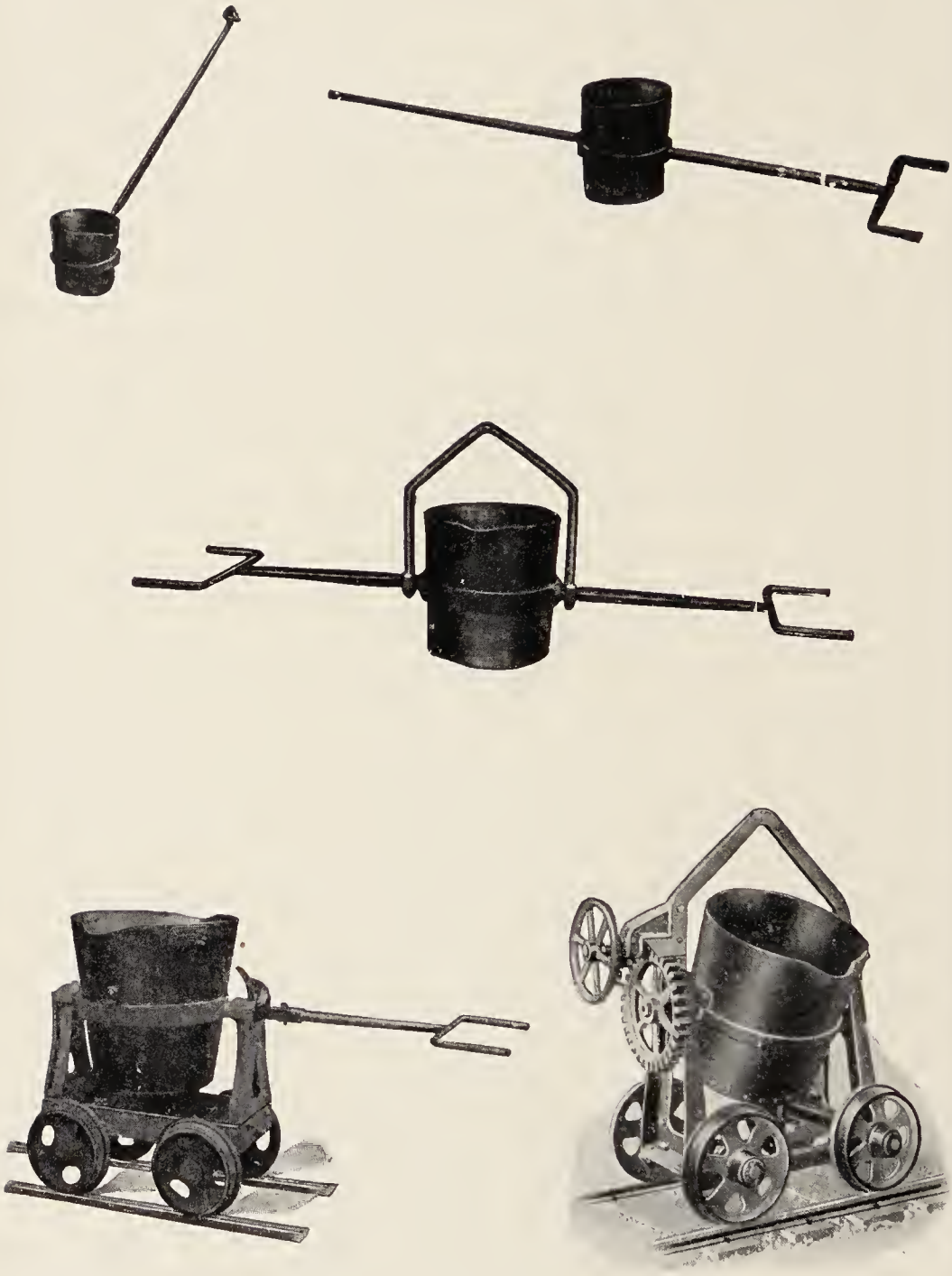
FIG. 222.—IRON CUPOLA.

the time and the metal allowed to flow out of the cupola and collect in an outside ladle as fast as it melts, the crucible zone will be very shallow, and the tuyeres will be situated not more than 2 to 5 in. above the bottom. If, on the other hand, the crucible is used as a reservoir for a large amount of metal, the tuyeres are placed correspondingly high. Hotter metal may be obtained by collecting the iron in an outside ladle, because it is not blown upon by the cold blast, and using the cupola as a reservoir is not considered good practice except for short intervals.

Tuyere Zone.—The tuyere zone is the place in which the blast comes in contact with, and burns, the red-hot coke. It is the zone of combustion, and all the heat of the operation should be produced in this place. It is of course situated near the tuyeres and wherever the raw blast may come in contact with coke. As there is always a column of coke extending to the very bottom of the cupola, combustion will begin immediately above the reservoir of melted metal. Its upper limit will depend upon the pressure of blast, because the greater the blast pressure, everything else being the same, the higher will it extend its zone of combustion. The blast pressure should be such, however, that the top of the tuyere zone, or zone of combustion, should never be more than 15 to 24 in. above the uppermost tuyeres.[1]

Melting Zone.—The melting zone is the space in which all the melting of iron takes place; it is situated immediately above the tuyere zone. During the melting, the iron is supported on a column of coke, which is the only solid material below the melting zone. When each layer or charge of iron enters the melting zone it should be about 15 to 24 in. above the uppermost tuyeres. As fast as it melts it trickles down over the column of coke to the bottom. It takes about five to ten minutes for each layer of iron to melt, however, and during this time the column of coke is burning and sinking. Therefore, the last of the iron will melt at a point about 7 in. lower than the first. Consequently, the melting zone overlaps the upper limit of the zone of combustion. If the layers of iron and coke are properly proportioned to the pressure of blast, each charge of iron will enter the top of the melting zone just before the next previous charge is completely melted at the bottom, and thus a continuous stream of iron will collect in the crucible or run from the tap-hole. Also, the coke

[1] There are sometimes two rows of tuyeres in cupolas; see Fig. 228.



FIGS. 223 TO 227.—FOUNDRY LADLES.

burned from the column will be exactly replenished each time by the layer of coke coming down, and the position of the melting zone, which is the important consideration, will be maintained within constant limits.

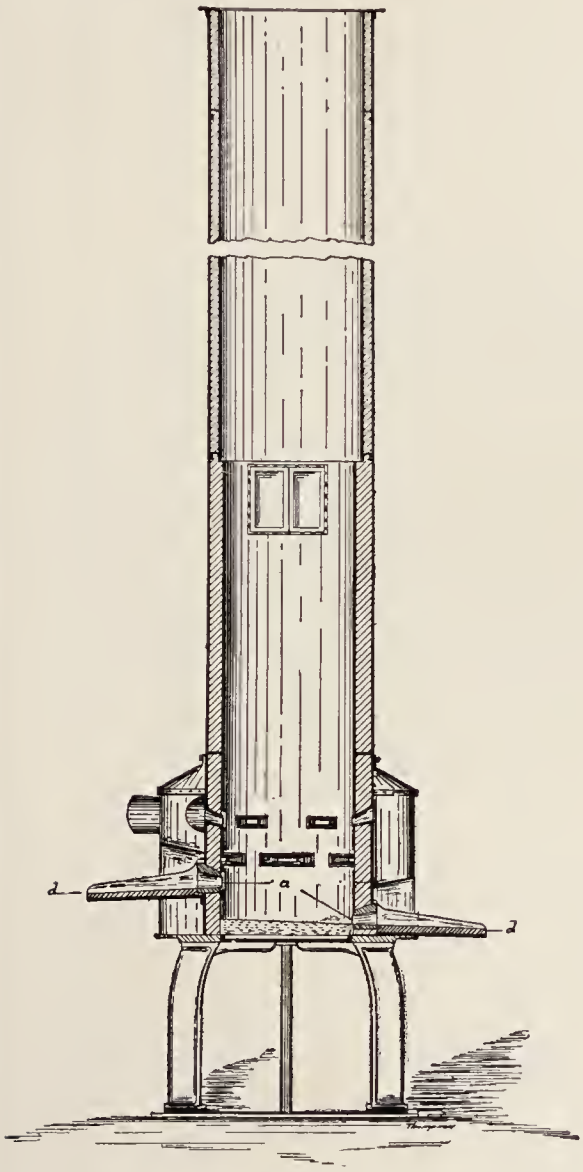


FIG. 228.

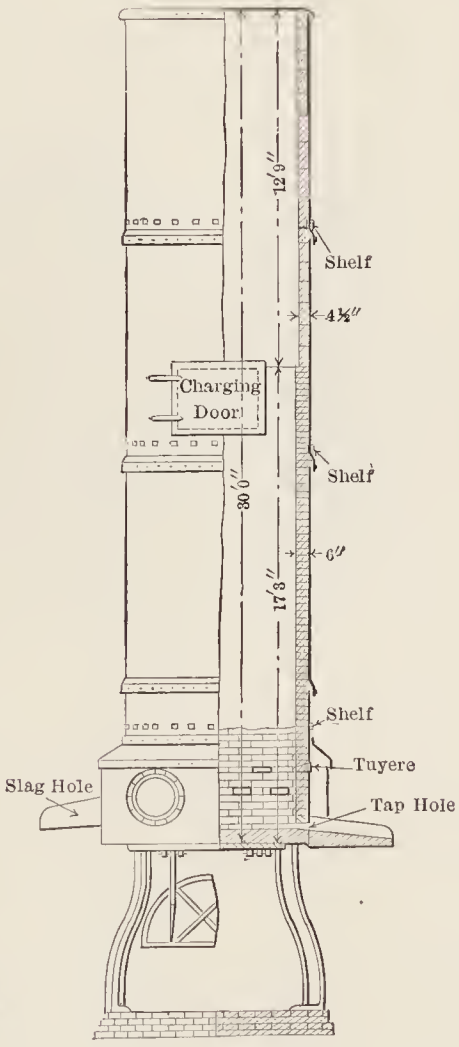


FIG. 229.

The actual position of the melting zone may always be learned when the cupola is emptied, because the iron oxide formed there will corrode the acid lining, which will therefore be cut away somewhat at this point. Corrections may then be made, if

necessary, in the next charge of the cupola. For example, the bed should be so proportioned that it will extend, after the coke is well heated up, to a point about 7 in. above the bottom of the combustion zone. The melting zone itself, as indicated by the cutting of the lining, should not be more than 8 to 12 in. deep.

Stack.—The stack extends above the melting zone to the level of the charging door. The function of this part of the furnace is to contain material that will absorb heat and thus prepare itself for the actions at lower levels, and that will also keep the heat down to the melting zone as well as possible.

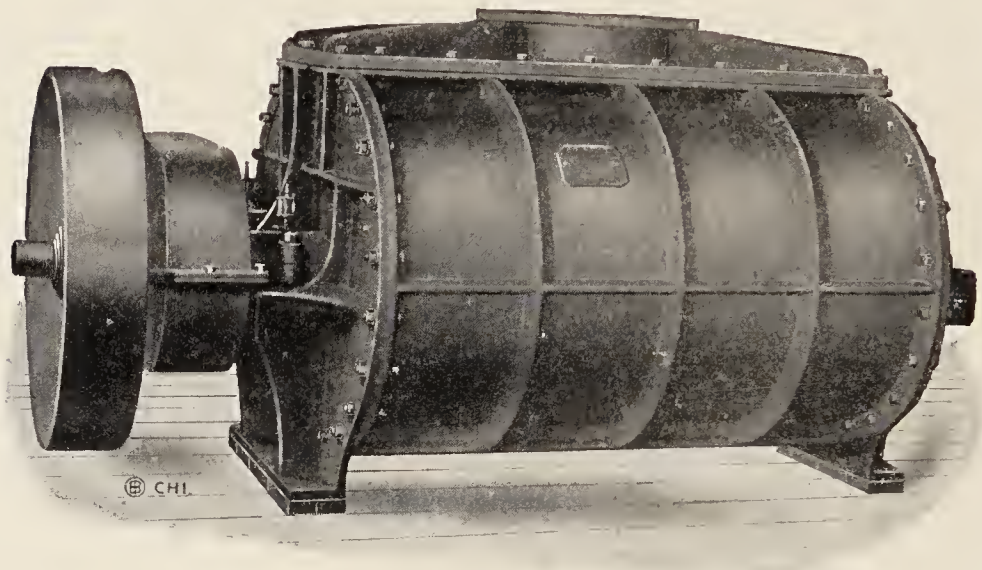


FIG. 230.—POSITIVE PRESSURE IMPELLOR BLOWER.

Tuyeres.—The blast enters the cupola through the tuyeres, of which there is usually one or two rows. The position of the upper row of tuyeres determines the position of the melting zone in the cupola. Two rows of tuyeres give faster melting in the cupola than one row, but cause greater oxidation and the consumption of more fuel on the bed, because the melting zone being higher in the cupola, requires a larger bed to start with.

Blast.—The blast pressure will depend somewhat upon the size of the cupola, but the present prevailing opinion is in favor of pressure not exceeding a pound, even for the very largest cupolas, and diminishing to half a pound or so for the smaller sizes. Fan-blowers, although cheaper, are giving place to pressure blowers, because if the former are opposed by pressure in

the cupola stack, they revolve without blowing any wind. The common type of blower used in America is of the two-impellor type, an example of which is shown in Fig. 230. It takes about 60 cu. ft. of air to burn a pound of coke, from which may be calculated the size of blower necessary for each cupola, allowing about 50 to 100 per cent. excess for leaks and incomplete combustion.

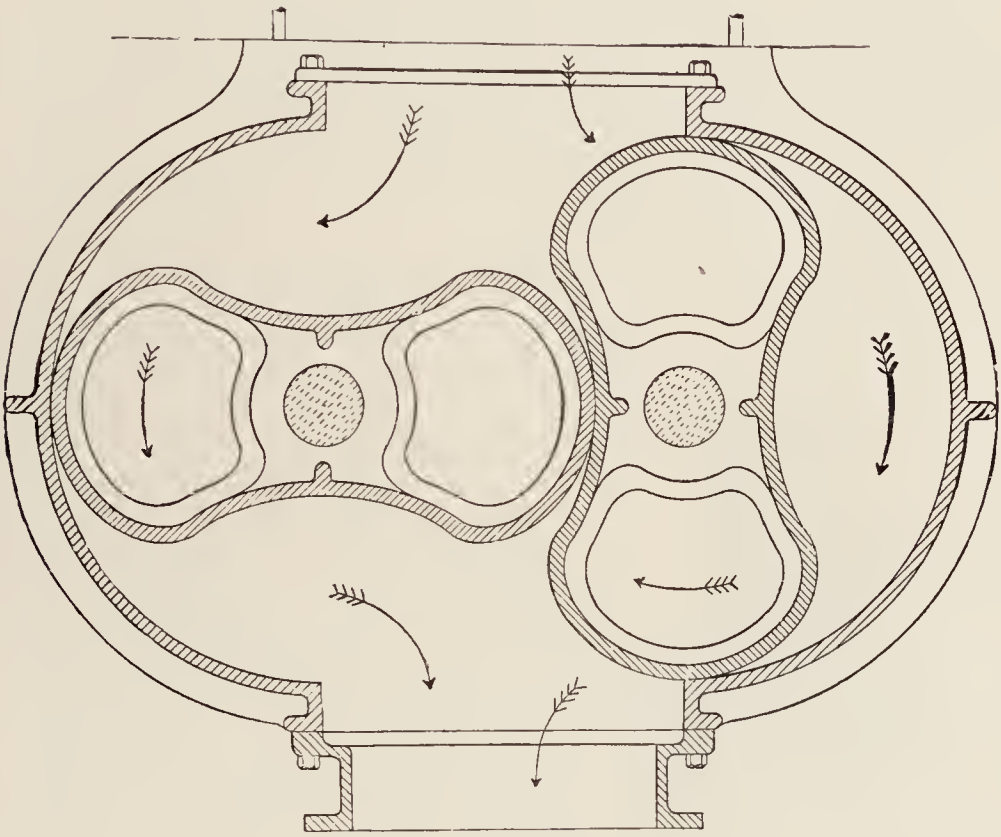


FIG. 231.

Makers of cupolas and blowers give all the necessary data in their catalogues, but advocate too high blast pressures and volumes, for obvious reasons. If the blast volume is too large, or the pressure is too great, the position of the melting zone will be too high. This means that the bed of coke must be larger to reach to the upper level of the melting zone, which is wasteful. It also means that the melted iron will have a greater height to drop through. It therefore oxidizes more, corrodes the cupola lining more, and consequently causes more waste of iron and more slag.

The volume of blast is the most important consideration, but this is difficult to measure, so the pressure is the substitute.

Loss.—The loss in melting will average about 2 to 4 per cent. It is made up of the silicon burned and the iron oxidized and carried away in the slag. There are other sources of loss in the foundry, such as a second loss of metal remelted—the sprues, risers, etc., which go back to the cupola in the form of scrap; metal spilled during pouring (which may amount to as much as 5 or 6 per cent. more), etc. In some foundries it is customary to pass the used floor sand through a magnetic concentrator, in order to recover the pellets of iron spilled during pouring, and important economy is sometimes obtained in this way. The total loss, that is, the difference in weight between pig iron bought and castings made, will probably be about 7 to 8 per cent. of the weight of the iron bought.

Scrap Used.—Scrap pig iron is often mixed with new pig iron for the manufacture of castings, both for the sake of economy and because the scrap iron has a somewhat closer grain or texture, which increases the strength of the mixture. The amount of scrap used will depend upon the materials to be manufactured. Cast-iron pipe is usually made without scrap, this industry amounting to between 500,000 and 800,000 tons per year in the United States alone. Stove foundries, on the other hand, use a very large amount of scrap as a rule, and jobbing foundries, in general, would probably use an average of 30 to 40 per cent. of outside scrap, besides the gates, sprues, bad castings, etc., made in their own foundries. The total production of gray-iron castings in the United States will represent about 75 per cent. pig iron and 25 per cent. bought scrap.

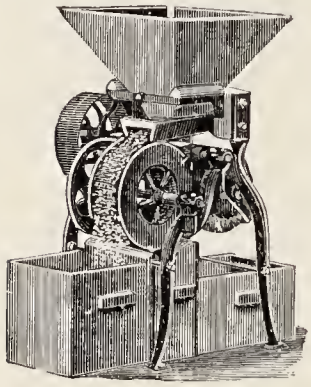


FIG. 232.—MAGNETIC CONCENTRATOR.

Cupola Run.—The campaign of an ordinary foundry cupola is only three or four hours long. As a general thing, the kindling is started about noon and allowed to burn with a natural draft until shortly after one o'clock, when the breast is closed and the blast put on. Metal is then received until four or five o'clock in the afternoon, when the last charge is melted. The supports are then pulled out from underneath the door closing the bottom of

the cupola, and the sand bottom, slag, coke, etc., left in the cupola is allowed to drop and is quenched with water. In order to allow plenty of room for the "drop" to fall, the cupola is usually elevated above the foundry floor.

Fuel.—The cupola is the cheapest furnace for melting because it affords direct contact between metal and fuel. The amount of fuel will be from one-fourth to one-twelfth of the weight of the iron melted, the former figure prevailing where exceedingly hot metal is desired—as, for example, for very small castings for malleable cast-iron work—and the latter figure where the melting is continued for several hours and the metal is not made very hot but is to be poured into large castings. Coke is the commonest fuel, with sometimes a mixture of coke and anthracite for the bed.

Cupola Charge.—In the cupola is first placed shavings and wood, on top of which is placed the bed of coke, which should be large enough to reach 15 to 24 in. above the uppermost tuyeres after the kindling is burned off. On top of this is placed a layer of pig iron about 6 in. thick, then another layer of coke about 7 in. thick, another layer of iron, and so on. The actual weight of the coke for the bed and of coke and iron for each charge will therefore depend directly upon the diameter of the cupola inside the brick lining, which varies from about 32 to 120 in., or even more in some cases. The weight of the coke in each layer will be about one-sixth to one-twelfth of the weight of iron in each layer. The tuyeres and front of the cupola around the tap-hole, known as the "breast," are left open for an hour or so after the kindling is lighted, in order that the draft may draw air in at that point for combustion. When the kindling is thus burned off and the bottom coke well lighted; the breast is closed and the wind turned on. It is very necessary that the bed should be well lighted and level. More recently it has become common practice to light the coke bed with a specially designed oil burner, instead of kindlings, which saves time and labor.

Cupola Melting.—The heat now generated by the combustion of coke begins to melt the iron, and in less than 15 minutes after the wind is put on the metal should begin to run from the open tap-hole. If it takes longer, then the coke bed was too high and wasteful. In 8 to 10 minutes thereafter the first layer of iron should be all melted. Now the second layer of iron lies upon the column of coke, whose top should again be 15 to 24 in. above the upper-

most tuyeres. If the layers of coke are too thick there will be a delay in the iron entering the melting zone and the extra coke burned will not have been used to the best account. If the layers of iron are too thick, the last of the layer will melt too near the tuyeres, which will oxidize it excessively and make it cold. This can be observed during the run by noting if the iron runs first hot and then cold. It is very important to watch the flame that comes off the top of the stack in the cupola. When the blast volume is too large this flame will be "cutting,"—i.e., oxidizing in character. Too great oxidation may also be observed if sparks of burning iron are projected from the slag-hole. If the layers of iron and coke are both too thick, there may be a correct relation between the weights of the two, but both of the irregularities mentioned above will be observed. It is probably not possible to have the alternate layers of fuel and iron too thin if the correct relation between them is maintained.[1] Of course, if very hot iron is required it will be necessary to have thicker layers of coke, and slower melting must be expected.

Chemical Changes.—As the iron drops down over the coke, it absorbs sulphur, the exact proportion depending chiefly upon the relative amount of coke and iron used and the per cent. of sulphur in the coke. It will vary from 0.02 to 0.035 per cent. of the iron; that is to say, if the pig iron charged contained 0.08 per cent. sulphur, there will be from 0.1 to 0.115 per cent. in the castings. The sulphur in the first iron will be higher than in that of the middle of the run, because of the extra amount of coke burned before the iron begins to come from the tap-hole. The last iron will also be somewhat higher in sulphur, because there is a larger loss of metal during the last of the run, when the oxidizing conditions are more intense, and therefore a concentration of sulphur. The best practice is to cut the blast off progressively as there is less stock in the cupola.

In many foundries it is customary to charge limestone, in the form of oyster shells, marble chippings, or crude limestone, and sometimes with it a little fluorspar (CaF_2), into the cupola. The amount of limestone varies greatly, but will average perhaps 1/2 to 1 1/2 per cent. of the weight of the metal. This limestone fluxes the dirt on the metal and the ash of the coke and carries off some sulphur in the slag. Fluorspar makes a somewhat more liquid slag than limestone alone and the more liquid slag is believed to ab-

[1] See an able paper by R. Moldenke, No. 96.

sorb a little more sulphur, and also to make the cupola "drop" more easily, i.e., dump its contents when the campaign is ended, and the bottom is allowed to fall. It also cuts the lining more.

As the metal melts and falls from the melting zone down in front of the tuyeres, it suffers oxidation, which carries iron oxide into the slag and also burns up silicon. The melted metal therefore contains from 0.25 to 0.4 per cent. less silicon than the original pig.[1] In other words, if the mixture charged contains 2.25 per cent. of silicon, the castings will contain 1.85 to 2 per cent. silicon.

Cupola Gases.—The gases coming out of the top of the cupola charge consist principally of nitrogen from the air, while the remainder is carbon dioxide—CO_2—and carbon monoxide—CO—with sometimes a little free oxygen. Free oxygen is evidence of a "cutting flame" and shows too great oxidation in the melting zone. Such a flame may be recognized without the aid of chemical analysis after a little practice by means of the eye. It is "sharper" looking than a richer flame and burns close to the top of the stock. One can identify it definitely by holding an iron rod in it for a while; after the iron becomes red hot it will oxidize much more rapidly in a cutting flame than in a reducing flame. Again, a reducing flame will usually not burn until it becomes mixed with the air sucked in at the charging door. All the carbon monoxide that goes out of the charge represents incomplete combustion and a waste of heat. It seems to be impossible to prevent this here, however, just as in the blast furnace, whose operations cupola melting resembles in some general respects. Several analyses of cupola gases are given in Table XVIII.

[1] With good practice it should be no more than 0.30 per cent. less.

TABLE A XVIII.—ANALYSIS OF CUPOLA GASES

Collected About 3 or 4 Feet Below the Charging Door

Time elapsed since blast was put on	Analysis by Volume				
	Oxygen O	Carbon dioxide CO_2	Carbonic oxide CO	Nitrogen (by difference) N	Ratio CO_2 is to CO as 1 is to:
10 minutes.	0.0	13.8	9.9	76.3	0.717
1 hour 13 minutes.	0.0	9.5	16.9	73.6	1.780
2 hours 17 minutes.	0.4	9.2	16.6	73.8	1.804
3 hours 13 minutes.	0.0	6.7	21.7	71.6	3.239
4 hours 15 minutes.	0.1	7.8	22.3	69.8	2.859
38 minutes.	1.8	7.6	15.5	75.1	2.04
1 hour 42 minutes.	2.8	7.5	13.3	76.4	1.77
2 hours 50 minutes.	1.9	7.1	15.8	75.2	2.225
3 hours 40 minutes.	0.1	7.2	19.0	73.7	2.64
38 minutes.	0.0	10.2	14.6	75.2	1.431
3 hours.....	2.9	5.4	14.3	77.4	2.65
10 minutes.	0.2	13.1	7.7	79.0	0.588
3 hours 10 minutes.	0.3	10.3	11.7	77.7	1.136
50 minutes.	0.0	7.1	15.4	77.5	2.17
1 hour 40 minutes.	0.0	8.3	13.5	78.2	1.626
2 hours 40 minutes.	0.0	8.2	12.1	79.7	1.475
3 hours 40 minutes.	0.0	6.0	15.0	79.0	2.50
45 minutes.	0.0	13.0	12.6	74.4	0.97
1 hour 40 minutes.	0.0	13.0	11.2	75.8	0.862
2 hours 40 minutes.	0.0	8.2	20.0	71.8	2.44
3 hours 50 minutes.	0.4	6.0	22.1	71.5	3.683
4 hours 43 minutes.	1.2	5.1	21.2	72.5	4.157
1 hour.....	0.0	9.8	15.4	74.8	1.571
1 hour 53 minutes.	0.0	9.1	16.8	74.1	1.846
2 hours 45 minutes.	0.0	8.8	16.8	74.4	1.91
3 hours 45 minutes.	0.0	7.5	19.7	72.8	2.627
4 hours 45 minutes.	0.0	7.5	18.7	73.8	2.500
Another Cupola					
30 minutes.	0.1	16.7	7.3	75.9	.437
1 hour 30 minutes.	0.1	13.1	10.7	76.1	.817
2 hours 38 minutes.	0.4	11.8	11.0	76.8	.932
3 hours 20 minutes.	0.0	12.8	7.7	79.5	.602

Burdening the Cupola.—It should be the duty of the foundry metallurgist or chemist to learn from his records, or other approximations, the amount and analysis of all the metal in the yard. The following table will, for example, show a convenient form of this record.

TABLE A XIX

Kind	Weight tons	Si	S	P	Mn	Price
High Sulphur, Southern	500	0.70	0.100	1.50	0.30	$18.00
High Silicon, Bessemer	60	2.50	0.025	0.07	0.60	25.00
X No. 1	100	3.00	0.030	0.80	1.25	24.00
No. 3 Foundry	150	1.75	0.070	0.30	0.60	22.50
Ferrosilicon A	30	10.00	0.040	0.50	0.10	35.00
Ferrosilicon B	30	50.00	0.003	0.04	.....	105.00
Machinery Scrap	100	1.70?	0.100?	1.00?	0.60?	19.00
Miscellaneous Scrap	300	1.50?	0.20?	1.40?	0.60?	15.00
Cast-iron Borings	100	1.50?	0.20?	1.40?	0.60?	11.00
Steel Scrap	100	0.10	0.07	0.10	0.60	13.00

The price should always be in evidence. It should not be the price at which the material was purchased but the market price at the time the iron is to be used. For instance, if a large amount of high grade pig iron had been contracted for a year previously and if meanwhile the price of pig iron had been rising, the purchase price of that pig iron would not represent its present value. From the current numbers of such trade periodicals as the *Iron Age* and the *Iron Trade Review*, one can always obtain the prevailing prices for the different grades of iron.

Suppose now with these irons it is desired to burden a 72-in. cupola with a mixture for making heavy hydraulic pumps for which a satisfactory analysis might be 1.60 per cent. silicon, 0.70 per cent. phosphorus, less than 0.10 per cent. sulphur and about 0.50 per cent. manganese. The first step is to calculate the cupola charges, and the chemist knows by experience with this particular cupola that it will lose 0.25 per cent. silicon and 0.10 per cent. manganese and it will gain 0.03 per cent. sulphur. The average analysis of the mixture put into the cupola must then be 1.85 per cent. silicon, 0.70 per cent. phosphorus, less than 0.07 per cent. sulphur and about 0.60 per cent. manganese.

The chemist also knows by calculation that about 5200 lb. of iron will give a layer of the proper thickness in a 72-in. cupola. His problem now is to make such a mixture of the available pig irons that their collective weight will be 5200 lb. and their average analysis as given above. Moreover if he is a good metallurgist he must aim at using as large an amount as possible of the cheapest materials.

He first considers the steel scrap, but knows he cannot use very much of this because too much coke would be required for getting iron of the requisite fluidity, but he estimates that 5 per cent. (say 200 lb.) will not increase harmfully the fuel necessary. This figure therefore comes at the top of his list (see Table XX).

Next he considers the use of machinery scrap, because he knows that his miscellaneous scrap and borings are too uncertain in analysis to be used in a mixture which must give pretty strong and non-porous castings. One thousand pounds of machinery scrap would be about 20 per cent. of his mixture, and he knows from experience that this is a fairly satisfactory proportion for scrap, so that figure goes down second in Table XX. The low price of the High Sulphur Southern Pig tempts him, but he realizes that he must offset the use of this material by some high silicon low sulphur iron. And in casting about for such a one he naturally considers first the X No. 1. He cannot use much of this either because of its high manganese and it seems reasonable to mix an equal amount of these two; the only question is, How much of this mixture will the cupola stand? To get an idea of this, he first calculates their average analysis and finds it to be 1.85 per cent. silicon, 0.065 per cent. sulphur, 1.15 per cent. phosphorus, and 0.78 per cent. manganese. Evidently the phosphorus is the only element in this mixture that gives him difficulty. Indeed, if that were not high he could make almost his whole charge up of these two irons and the scrap. The phosphorus in this mixture is 0.45 per cent. higher than that of his desired mixture. Therefore he knows that he must use a good deal of No. 3 Foundry iron to bring this element down. The phosphorus in the No. 3 Foundry iron is about as much below the desired phosphorus as that in the mixture of the High Sulphur Southern and the X No. 1 is above it. He must not forget, however, that he has already used 1000 lb. of machinery scrap containing probably 1 per cent. of phosphorus. Therefore he must use a correspondingly larger amount of No. 3 iron to offset this also.

As a first estimate he therefore considers using 800 lb. of High Sulphur Southern, 800 lb. of X No. 1, and 2400 lb. of No. 3 Foundry—that is, once and a half as much No. 3 as the mixture of the other two. But a little reflection tells him that this mixture is going to be too low in silicon, because the mixture of High Sulphur Southern and X No. 1 only gave us 1.85 per cent. silicon, while the No. 3 Foundry and the machinery scrap are both below that. There are then three ways open to him. He may use a little Ferrosilicon A or he may pound up a little Ferrosilicon B and dissolve it in the ladle of iron or he may use a little High Silicon Bessemer iron. Either of these methods would do, but the writer would prefer to use the High Silicon Bessemer because this will have the effect of cutting the sulphur and phosphorus down and the expense is practically the same. (It requires such a small amount of ferrosilicon to give the desired silicon in the mixture that the expense of using it is very small, in spite of its price.) Consequently we put down the weights shown in the second column of Table XX, and we now figure out the weight of silicon, sulphur, phosphorus, and manganese in the mixture by the methods indicated there, and the average percentage of each element. The latter figures show us that the silicon is too low, and a simple calculation shows us that we need 5 lb. more in the total weight of silicon. We can get this by increasing the amount of either High Silicon Bessemer or of X No. 1, and correspondingly decreasing the No. 3 Foundry. The High Silicon Bessemer has 0.75 per cent. more silicon than the No. 3, so it would take (5 lb. $\div 0.75$ per cent. =) about 650 lb. change to make up the difference in this way. The X No. 1 has 1.25 per cent. more silicon than the No. 3, so it would take (5 lb. $\div 1.25 =$) 400 lb. change to make up the difference in this way. We naturally would prefer to use the latter, being cheaper, and if we think we can stand all that extra manganese in our castings we probably will do so; if not, we will have to use altogether 1000 lb. of High Silicon Bessemer and only 1400 lb. of No. 3 Foundry. We then make up a new table similar to Table XX and figure out the average analysis as before. It should now come about right.

TABLE A XX

Kind	Weight Lb.	Analysis				Weight of [1]			
		Silicon %	Sulphur %	Phosphorus %	Manganese %	Silicon	Sulphur	Phosphorus	Manganese
Steel scrap	200	0.10	0.07	0.10	0.60	0.2	0.14	0.2	1.2
Machinery scrap	1000	1.70?	0.100?	1.00?	0.60?	17.0	1.00	10.0	6.0
High Sulphur Southern	800	0.70	0.100	1.50	0.30	5.6	0.80	12.0	2.4
X No. 1	800	3.00	0.030	0.80	1.25	24.0	0.24	6.4	10.0
No. 3 Foundry	2000	1.75	0.070	0.30	0.60	35.0	1.40	6.0	12.0
High Silicon Bessemer	400	2.50	0.025	0.07	0.60	10.0	0.10	0.3	2.4
Total weights	5200					91.8	3.68	34.9	34.0
Average percentage[2]						1.77%[2]	0.071[2]	0.67[2]	0.65[2]

[1] Multiply the weight of each kind of material by the percentage of the elements in it. [2] Divide each total weight of element by 5200 lb.

Comparative Cupola Practice

In Table XXI are shown some figures on Comparative Cupola Practice which confirm in a striking way the rules laid down above, and add new light on the subject.

Fuel.—The first lesson we learn from the table is that a mixture of coal and coke and inferior coke give slow melting and a poor fuel ratio. Indeed, the work of the cupola using these grades of fuel is so far inferior to the others that I have separated them in Table XXI and omitted them from all my calculations. After a careful study of the figures, we are strengthened in the opinion that a mixture of coal and coke has nothing to recommend it except a deceptive first cost.

Tuyere Ratio.—The next most striking evidence produced by the figures is the relation between the tuyere area and the speed of melting: if we average up the iron melted per minute in the cupolas whose area is less than 6.56 times the tuyere area we obtain a figure of 22.56 lb.; if we get the corresponding figure for the cupolas with lesser proportionate tuyere area, we obtain 18.57 lb. Indeed so striking is the relation that there is only one exception, namely, cupola No. 8, and we need not look far for a reason for the slow melting in this cupola. It is evidently due to the short height of stack which causes the iron to reach the melting zone before it has been sufficiently preheated. A large proportionate tuyere area evidently means that the wind will pass through the tuyeres with less resistance and a lower velocity. That is to say, we will get more wind and it will not be driven so much to the center of the cupola. It may be said to be established for the types of practice here exhibited that the collective area of the tuyeres should not be less than one-sixth, and preferably not less than one-quarter, of the horizontal area of section of the cupola.

Height of Stack.—There is also an important relation between the speed of melting and the height of the charging door above the tuyeres divided by the diameter of the cupola. The average speed of melting of the cupolas, where this ratio is greater than 2.5, is 24.12 lb. per minute, while the average speed of melting of those whose ratio is less than 2.5 is only 19. 15 lb. per minute. There are only two exceptions to this rule: (1) Cupola No. 6 is a fast melter, but this is doubtless due to the large proportionate tuyere area. (2) Cupola No. 3 is a slow melter, but this is doubt-

TABLE XXI.—COMPARATIVE CUPOLA PRACTICE

	1	2	3	4	5
Diameter of cupola, inches	27	35	42	44	54
Height of tuyeres from sand bottom, inches	12	7	11	12	7.5
Height of charging door above tuyeres, inches	106	120	139	109	103.5
Height of charging door above tuyeres divided by diameter	4.0	3.4	3.3	2.5	1.9
Number of tuyeres	6	6	6	.....	6
Size of tuyeres, inches, vertical X horizontal	4x6	5x5	4x6	.....	4½x13
Area of tuyeres, square inches	144	170	144	336	348
Cupola area is how many times tuyere area	3.97	5.66[2]	9.62	4.53	6.58
Diameter of blast pipe, inches	8	16	14	15	17
Blast pressure, ounces, 20 minutes after start	9	16	8	9 1/2	13
Class of work made	Job	Plate	Light Job	Boiler & Plate	Stove Plate
Lined up how often? Months	.....	6	6	6	6
Weight of fuel on bed, pounds	350	650	650	1,300	1,400
Weight of iron on bed, pounds	700	1,300	1,400	3,000	3,000
Weight of fuel in charges subsequent to the bed, pounds	90	125	100	175	300
Weight of iron in charges subsequent to the bed, pounds	400	1,300	1,000	2,000	3,000
Total weight of fuel, pounds	2,000	1,850	2,150	3,075	4,800
Total weight of iron, pounds	8,000	14,000	16,000	27,000	33,000
Ratio of fuel on bed, above tuyeres, to iron on bed, 1 is to	3.2	2.8	3.5	3.2	3.7
Ratio of fuel to iron, later charges	4.4	10.4	10.0	11.4	10.0
One pound fuel melts how many pounds iron	4.0	7.5	7.6	8.8	6.9
Kind of fuel used	Coke	Coke	Coke	Coke	Coke
Fuel weighed or measured	W	W	M	W	W
Height of fuel bed above tuyeres, inches	20	21[1]	15	33	24
Thickness of fuel, charges after the bed, inches	8.4	7.0	3.8	6.1	6.9
Thickness of iron charges after the bed, inches	3.3	6.5	3.5	6.3	6.3

[1] Two rows of tuyeres.

TABLE XXI.—COMPARATIVE CUPOLA PRACTICE.—*Continued.*

	1	2	3	4	5
Time before iron comes after blast is on, minutes	7	15	5	15	10
Time to melt each iron charge after the bed, minutes	3.25	8.5	5.7	9	10
Total iron melted per minute, pounds	123	155	175	225	300
Total iron melted per minute, per square foot cupola area	30.98	23.20	18.19	21.30	18.87

	6	7	8	9	10	11
Diameter of cupola, inches	54	56	58	60	60	72
Height of tuyeres from sand bottom, inches	14	25	16	2	12	24
Height of charging door above tuyeres, inches	113	141	92	112	114	142
Height of charging door above tuyeres divided by diameter	2.1	2.5	1.6	1.9	1.9	2.0
Number of tuyeres	6	12	6	8	6	.....
Size of tuyeres, inches, vertical X horizontal	10x7	6x12	7x12	4½x7½	7x10	.....
Area of tuyeres, square inches	420	864	546	270	420	706
Cupola area is how many times tuyere area	5.45	2.85	4.83[1]	10.47	6.73	5.76
Diameter of blast pipe, inches	18	24	20	18	18	24
Blast pressure, ounces, 20 minutes after start	14	16	16	8	8	13½
Class of work made	Boiler & Radiator	Rolls	Pipe Ft'g & Job	Plate	Sanitary & Plate	Electrical
Lined up how often? Months	10	8 to 10	7	6	12	6
Weight of fuel on bed, pounds	2,000	3,000	2,000	1,700	1,800	2,500
Weight of iron on bed, pounds	6,000	9,000	6,000	6,000	5,000	7,000
Weight of fuel in charges subsequent to the bed, pounds	450	450	400	200	350	600
Weight of iron in charges subsequent to the bed, pounds	4,000	4,500	4,000	2,000	4,000	7,600

[1] Two rows of tuyeres.

(For averages, see next page.)

TABLE XXI.—COMPARATIVE CUPOLA PRACTICE.—*Continued*

	6	7	8	9	10	11
Total weight of fuel, pounds	8,500	12,000	4,400	6,600	6,600	12,700
Total weight of iron, pounds	64,800	100,000	30,000	49,500	50,000	127,500
Ratio of fuel on bed, above tuyeres, to iron on bed, 1 is to	4.3	5.0	5.0	3.8	4.7	5.4
Ratio of fuel to iron, later charges	8.8	10.0	4.1	10.0	11.4	11.7
One pound fuel melts how many pounds iron	7.5	8.3	6.8	7.5	7.6	10.0
Kind of fuel used	Coke	Coke	Coke	Coke	Coke	Solvay Coke
Fuel weighed or measured	M	W	W	M	W	W
Height of fuel bed above tuyeres, inches	32	40	14[1]	30	22	6
Thickness of fuel, charges after the bed, inches	10.4	9.6	8.0	3.8	6.5	7.8
Thickness of iron charges after the bed, inches	8.4	8.8	7.3	3.4	6.8	9
Time before iron comes after blast is on, minutes	20	5	15	1	15	15
Time to melt each iron charge after the bed, minutes	11	12	12	5.5	11	13.5
Total iron melted per minute, pounds	360	370	333	367	360	567
Total iron melted per minute, per square foot cupola area	22.64	21.60	18.14	18.80	18.40	20.06

	A1	A2	A3	A4	Averages
Diameter of cupola, inches	32	42	44	48	.....
Height of tuyeres from sand bottom, inches	11	12	9.5	14	12.6[1]
Height of charging door above tuyeres, inches	133	132	84.5	103	116
Height of charging door above tuyeres divided by diameter	4.1	3.1	1.9	2.1	2.5[2]
Number of tuyeres	6	6	8	6	.....
Size of tuyeres, inches, vertical X horizontal	4½x6	4x10	2¼x11	4x6	.....

[1] Including A1, A2, A3, A4.

[2] Excluding A1, A2, A3, A4.

TABLE XXI.—COMPARATIVE CUPOLA PRACTICE.—*Continued.*

	A1	A2	A3	A4	Averages
Area of tuyeres, square inches..	162	240	198	144	.....
Cupola area is how many times tuyere area.....	4.96	5.77	7.68	12.56	6.56[1]
Diameter of blast pipe, inches.	12	14	12	16	.....
Blast pressure, ounces, 20 minutes after start.....	16	12	13	8	12[1]
Class of work made.....	Gas Engine	Job	Pumps & Job	Medium Light	
Lined up how often? Months.	6	.....	3	6	.....
Weight of fuel on bed, pounds.	450	1,000	1,000	1,300	.....
Weight of iron on bed, pounds.	1,000	4,500	1,000	4,000	.....
Weight of fuel in charges subsequent to the bed, pounds...	110	250	110	200	.....
Weight of iron in charges subsequent to the bed, pounds...	1,000	2,000	1,500	2,000	.....
Total weight of fuel, pounds...	1,250	1,935	2,040	4,100	.....
Total weight of iron, pounds...	8,000	12,000	14,800	32,000	.....
Ratio of fuel on bed, above tuyeres, to iron on bed, 1 is to	3.5	8.6	1.6	5.0	4.2
Ratio of fuel to iron, later charges.....	8.7	8.0	13.6	10.0	9.5
One pound fuel melts how many pounds iron.....	6.4	6.2	7.2	7.8	7.3[1]
Kind of fuel used.....	Light Coke	Coal & Coke	Coal & Coke	Coal & Coal	
Fuel weighed or measured.....	M	M	W	M	
Height of fuel bed above tuyeres, inches.....	21	11	25	22.5	22.5[1]
Thickness of fuel, charges after the bed, inches.....	7.3	9.5	3.9	5.8	7.0[1]
Thickness of iron charges after the bed, inches.....	6	7	4.7	5.3	6.4[1]
Time before iron comes after blast is on, minutes.....	10	15	15	7	11.3[1]
Time to melt each iron charge after the bed, minutes.....	7.7	.....	9.5	13.8	9.46[1]
Total iron melted per minute, pounds.....	57	.....	164	145	.....
Total iron melted per minute, per square foot cupola area..	10.2	.....	15.53	11.54	21.11[2]

[1] Including A1, A2, A3, A4. [2] Excluding A1, A2, A3, A4.

less due to the very small proportionate tuyere area. With these exceptions the rule is universal and a comparison of different cupolas one with another only strengthens it; for example, 4 with 8, the proportionate tuyere area being nearly the same; also 2 with 6, etc. A comparison of 3 with 9 is an apparent exception which is perhaps explained by the low tuyeres in No. 9.

Blast Pressure.—The average speed of melting of the cupolas with more than 12 oz. blast pressure is only 20.75 lb. per minute, while that with less than 12 oz. is 21.53. This relation is not so striking as to establish a rule, especially as a single cupola (No. 1) throws such a large influence into the low-blast column. Nevertheless, the evidence is sufficiently striking to discredit the theory that higher blast pressure necessarily gives faster melting. Indeed, if cupolas 3, 9, and 10 had a larger tuyere area, we should expect an average result very favorable to low blast pressure.

Height of Fuel Bed.—The original height of fuel bed is no criterion with which to figure as it in many cases is raised or lowered during the first few minutes of melting, and thereafter occupies some other position. It is the thickness of the fuel and iron charges after the bed which is the important consideration and, as already observed, these should be regulated to about 6 to 8 in. for fuel and 6 in. for iron irrespective of the diameter of the cupola. In case hot iron is desired the layer of fuel should be at the upper limit of thickness and vice versa.

Speed of Melting.--The speed of melting is very important, because everything else being equal the faster the melting per square foot of cupola area the greater will be the efficiency of operation of the cupola, and therefore of economy under the given conditions.

Melting Steel For Castings

Steel castings are made in (1) acid open-hearth furnaces, (2) basic open-hearth furnaces, (3) small Bessemer converters of special design, and (4) crucibles. The castings are made from the metal just as it comes from the steel furnace, and the processes are mentioned above in the order of relative production.

Open-hearth Furnaces.—The making of steel for castings is practically the same as making steel for ingots, except that foundry furnaces are of smaller size, varying on the average

from 5 to 30 tons. In some cases furnaces smaller than this are used, but it is generally believed that circumstances rarely warrant this, since the expense of running the small furnaces is large in proportion. The chief difference in practice is that the temperature for steel-casting work is hotter than when ingots are made. Therefore furnace repairs are higher and the life shorter. In ordinary open-hearth foundry work the purification is continued to the point where the steel contains about 0.18 to 0.28 per cent. carbon after recarburizing, while the silicon will be usually 0.20 to 0.30 per cent.

Acid versus Basic Open-hearth Steel.—In steel castings it is necessary to have somewhat lower phosphorus and sulphur than in ingots, because the metal is not to receive the beneficial effect of mechanical work, and therefore must be purer in order to have a good degree of strength and ductility. Consequently, if we use an acid steel-making process, we must start with very low phosphorus and low sulphur pig iron, which is costly and becomes more so each year in America. For this reason the Bessemer and the acid open-hearth steel-making processes are more expensive for casting work than the basic open-hearth. The result is a present rapid increase in the use of basic open-hearth steel in America as well as in Germany, with a probability that in a few years it will be the predominant process for this purpose. This is in spite of the fact that basic steel has very serious disadvantages, chief among which are the amount of oxygen contained in it at the end of the process and the difficulty of keeping the desired amount of silicon in it during teeming, both of which conditions increase the liability to blow-holes, which are especially objectionable in castings, as there is no opportunity of their being welded up and as castings may have to be discarded on this account after a good deal of expensive machine-work has been done. On this account the acid open-hearth process has long held the predominant position in the steel-casting industry. In fact, this is the only place where the acid open-hearth process now finds important employment on a large scale in this country.

Bessemer versus Open-hearth.—The open-hearth furnace gives a large amount of steel at long intervals, which is very inconvenient for foundry work, because the molds necessary to take all the metal must be stored upon the foundry floor until the heat is ready to pour, and then those who are to do the teeming must

interrupt their other work for half an hour or more for this purpose. Even where the foundry is large enough to have many furnaces, there is no surety that they will come out at regular and short intervals, because the operation in one may be delayed. Another disadvantage of the open-hearth process is that, in order to be economical, it must be operated continuously day and night, which also is inconvenient for foundry work. Further, it is not possible to get the metal as hot as desired without great damage to the furnace, which is subjected to a higher temperature than the metal. Lastly, since hot metal is desirable for all castings except those of very large size, it is usually necessary to tap all the metal from the furnace at once, and recarburize it at once, which prevents castings of special analysis being made, unless ordered in very large quantities. Nowadays, a great many nickel-steel castings are made in open-hearth furnaces, but this requires nice calculations, so that the castings molded shall be just equal to the capacity of the heat, and usually results in a certain amount of scrapping of high-class metal.

All these objections are avoided in making castings in Bessemer converters, but they too have their great disadvantages, chief among which is greater cost. The latter is due principally to the amount of waste in the side-blown converters used for this purpose, and the greater cost of the pig iron used, which must be low in phosphorus and sulphur. Small converter plants are so very cheap—costing less than $5000 for apparatus—that a great many iron-foundries in the United Sates are putting them in as an adjunct to their cupola process, in order that they may be able to make steel castings at will. The amount of capital tied up is so small, and there being no important expense in starting and stopping the converter as often as desired, they can do this economically.

Tropenas Converter.—The largest number of converters for steel-casting work are of the Tropenas type, in which the wind enters the vessel from seven tuyeres on the side, and the converter is tipped in such a manner that the streams of air are deflected onto the top of the bath. The impurities are oxidized as in the regular Bessemer process, except that the action is not quite so rapid, and the carbon is burned to carbon dioxide instead of carbon monoxide, which generates a much larger amount of heat:

$$C + O = CO \quad \text{(generates 29,160 calories).}$$
$$C + 2O = CO_2 \quad \text{(generates 97,200 calories).}$$

The pig iron used for these converters runs frequently above 2 per cent. of silicon, and this, together with the formation of carbon dioxide, results in very hot and fluid steel, which can be poured into castings of almost any small size. The blows usually last about 15 to 20 minutes, and the loss is from 17 to 20 per cent. of the weight of pig iron charged into the cupola in which it is melted. The vessel can be started up and stopped with very little expense, and this advantage over the open-hearth, together with the small amount of capital necessary to build the converter plant and the other conditions already mentioned, has caused many of these converters to be installed in America, and several in France, England, and other countries.

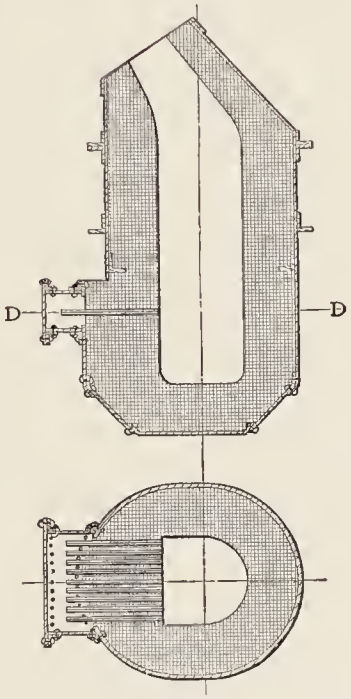


FIG. 233.—SECTIONS OF LONG-TUYERE CONVERTER.

The great disadvantages of the Tropenas converter are the waste and the cost for making repairs. Slight patching can be done through the mouth, but there is a hole in the front of the converter shell, closed by a movable steel plate, through which the operator can dig his way into the interior to perform the necessary repairs. As the lining in the neighborhood of the tuyeres is usually worn out in less than twenty blows, this costly method of lining is a serious drawback.

Long Tuyere Converter.—Next to the Tropenas, the greater number of converters at work in America are of the Long-Tuyere, or Stoughton, type, devised by the writer. The bottom part of this vessel is attached to the trunnion-ring by a method similar to that used for regular Bessemer bottoms, and may be removed with great ease, thus cheapening and facilitating repairs. Moreover, the chief repairs are in the bottom part at the mouths of the tuyeres, and therefore the lining of the upper part does not have to be relined completely for several months, although slight patching is necessary every twenty-five to thirty blows, when the bottom is changed. This converter is arranged to have but one row of tuyeres, discharging the blast immediately at the surface of

the metal, and the lining on the tuyere side is thicker in order that the tuyeres may be increased in length, which decreases the loss of metal during the process. The excessive loss in the side-blown converters is due chiefly to the spitting, which is very large, especially when the tuyeres have become worn away to a short length and the streams of air are badly directed and set up interfering currents.

Another cause of the excessive loss is the large amount of slag formed, because more iron is oxidized, and this corrodes the lining very rapidly. Part of the iron is oxidized at the mouths of the tuyeres, and another part is oxidized when the violent agitation of the bath, which occurs in all of these converters, especially during the boil, throws the metal up into the stack, where it meets free oxygen. The loss in the Long-Tuyere modification is 14 to 16 per cent., including cupola loss.

Sizes Used.—Most of the small converters have a capacity of about 2 tons, because this is economical and well proportioned to the capacity of an ordinary foundry. There are some 4- and 5-ton converters, however, and some of less than 1 ton capacity. Sizes less than 2 tons are costly to operate in proportion to their output. The blast pressure usually employed is 3 to 5 lb., with an average of about 3 3/4 lb.

TABLE XXII.—ANALYSES OF SIDE-BLOWN CONVERTER-GASES.

Sample No.	Time after Beginning of Blow	Analyses—Per cent.				Calculations from Analyses—Per cent.			
		CO	CO_2	O	N and H	Total O	N[1]	O entering	O Burning Si and Fe and Mn
1	4 min., flame starts..	0.0	8.2	1.1	90.7	7.1	88.7	23.6	16.5
2	10 min., boiling.....	0.3	24.3	0.4	75.0	18.3	73.0	19.4	1.1
3	12 min., shortening[2]...	0.4	8.8	0.2	90.6	6.8	88.6	23.5	16.7
4	17 min., after first drop	10.7	13.0	0.2	76.1	15.8	74.1	19.7	3.9
...	21 min., end of blow..								

[1] By difference, H being estimated as 2 per cent.

[2] I.e., just before the first drop. There are two drops to the flame in this operation, the second marking the end.

X

THE SOLUTION THEORY OF IRON AND STEEL

Scientifically considered, all of the members of the iron and steel series are alloys of iron and carbon. Therefore a study of the general theory of alloys leads to important information upon iron and steel. According to the authoritative definition, "a metallic alloy is a substance possessing the general physical properties of a metal, but consisting of two or more metals, or of metals with non-metallic bodies, in intimate mixture, solution, or combination with one another, forming, when melted, a homogeneous fluid." It will be seen from this that the essential feature of an alloy is that, when melted, it shall form a homogeneous fluid. In plain language, this means that, when melted, the different components are dissolved in one another. Melted alloys, therefore, come under the general head of solutions. In fact, the great bulk of our alloys, and especially of iron and steel, are produced by first dissolving the melted components and then allowing them to freeze. The laws governing this freezing, or solidification, have been known only a few years, and if this new knowledge has made great revolutions in physical chemistry, it has led to no less important discoveries in regard to the nature of iron and steel.

Solid Solutions.—Suppose first we have two metals that are soluble in each other when liquid, and also when solid. In other words, the metals of the alloy will be just as completely dissolved in each other after solidification as before. They will then form a "solid solution," and a solid solution bears practically the same relation to a liquid solution as a solid pure metal does to the same metal when liquid. For example, gold and silver dissolve in each other when liquid, and also when solid, in any proportion. Consequently any solution of these metals will cool to the freezing-point and then solidify without there being any important change (from the metallurgical or practical standpoint) in the relations of the two metals after the freezing. The reason that these solid solutions form in any proportion is that the two metals crystallize

alike. It is, perhaps, a new thought to the reader, but it is nevertheless true, that a metal forms a crystal whenever it solidifies. Furthermore, each metal has a particular, general shape which its crystals assume, and there is almost no force powerful enough to prevent them from taking that shape in preference to any other.

Tiny as the crystals sometimes are—often requiring the highest powers of the microscope to reveal them—their crystalline forces are very powerful. If, therefore, two metals do not form like crystals, they cannot solidify in solution, *i.e.*, in the same crystal, but freezing must be accompanied by separation.

By European metallurgists solid solutions are often called "mixed crystals," or "isomorphous mixtures," but this terminology is objected to because the relation of two substances when dissolved is far more intimate than any mixture possibly could be. In a mixture, the microscope will always be powerful enough to distinguish the different components, but a solution always appears like a s mple uniform body. Furthermore, the properties of a mixture are intermediate between the properties of its components, but a solution—either liquid or solid—has some properties which are different from any of the properties of either of its components. Again, the components of a solution are held together by chemical forces, while the components of a mixture are either not held together at all, or only because of close mechanical association. In brief, a solution has some of the characteristics of a chemical compound, and differs from such a compound chiefly because the latter must always be composed of definite amounts of each component, and in some multiple of their atomic weights, while a solution may contain widely varying amounts of each component.

Freezing of Solid Solutions.—When metals form solid solutions, the solutions freeze more or less like pure metals. In Fig. 240. I have shown graphically the freezing of all the alloys of gold and silver, extending from no silver (*i.e.*, 100 per cent. gold) to no gold (100 per cent. silver). This figure has been drawn from results obtained by experiment. The proportion of silver is shown by the abscissæ, or the horizontal distance away from the axis *OC*, and the temperature is shown by the ordinates, or the vertical distance away from the axis *OO*. In other words, any point between these two axes represents by one axis distance the composition of the alloy in silver and gold, and by the other, the temperature at which the alloy is at the moment. For

example, the point marked *a* is a certain distance from the axis *OC*, which shows that the alloy in question contains 50 per cent. of silver; it is also a certain distance above the axis *OO*, which shows that the alloy is now at a temperature of 1100° C.(2012° F.).

Since there is nothing in the alloys but silver and gold, the percentage of gold in each is 100 minus the percentage of silver. The horizontal distances therefore show the percentage of gold as well as of silver, and this is given in the second line of figures under the table.

Suppose we have a solution of 50 per cent. of silver and 50 per cent. gold at a temperature of 1100° C. It is represented at the point *a*, and is now liquid. When it cools to about 1035° C. it

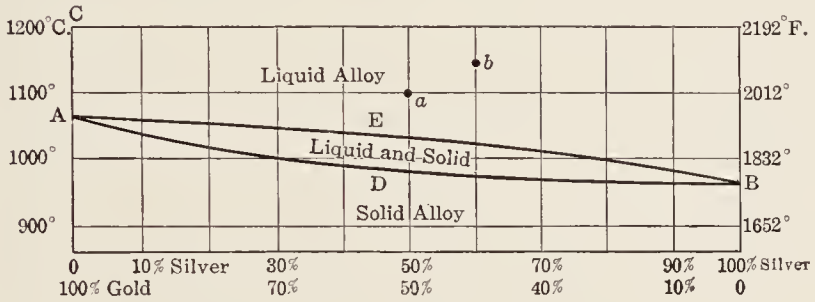


FIG. 240.—FREEZING CURVE OF THE GOLD-SILVER ALLOYS.

begins to freeze. It does not all freeze at the same time, but first some solid crystals freeze out and we have a mixture of solid crystals with liquid solution. The more the mass cools the more solid crystals there will be, each crystal being a solid solution of gold and silver. It is not until we reach a temperature of 985° C., however, that the last liquid freezes, and then we have a solid solution of gold and silver, the two solid metals now bearing practically the same relation to each other chemically that they did when liquid.

It will be noticed that when this alloy cooled from the point *a* to 1035°, it met the line *A E B*. This is the line that represents the beginning of freezing for all the gold-silver alloys. It has been drawn after many experiments have been made to show where it lies in the diagram. It will furthermore be noticed that when this alloy cooled to 985°, it met the line *A D B*. This is the line that represents the completion of freezing for all the gold-silver alloys, and its position has been learned from many experiments.

Take now the alloy containing 60 per cent. silver and 40 per cent. gold, at a temperature of 1150° C.—the point *b*. As this cools to a temperature of 1025° C., it meets the line *A E B* and freezing begins in the same way as before. Solid crystals form more and more as the alloy cools further, until we meet the line *A D B* at a temperature of 980° C. At this point the last liquid freezes.

The Freezing of Alloys of Lead and Tin

1. Suppose now, on the other hand, we have two metals which are soluble in each other when melted, but not when solid. Evidently there cannot be the same results as those described in the case of the gold-silver alloys. Such a series is found in the alloys of lead and tin, whose freezing is shown graphically in Fig. 241.

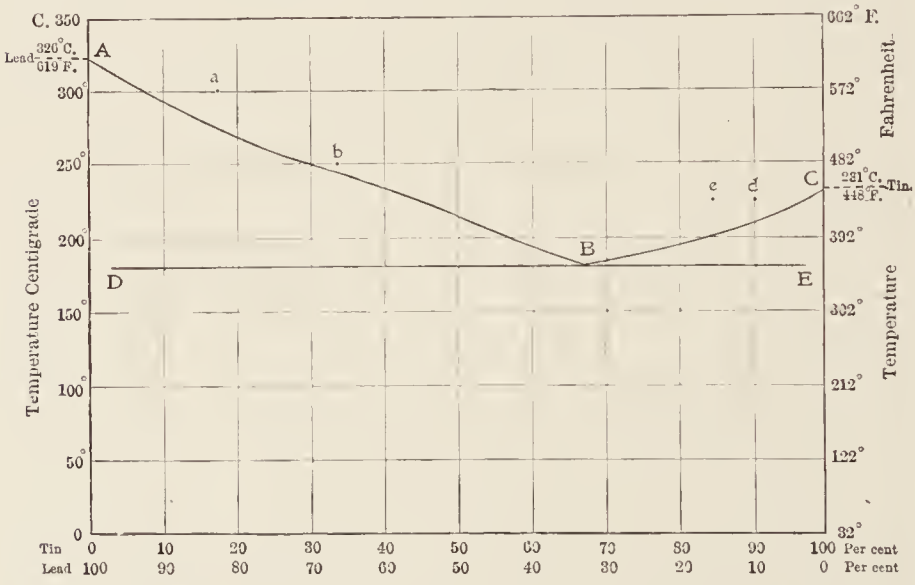


FIG. 241.—THE FREEZING OF ALLOYS OF LEAD AND TIN.

Here again I have shown the percentage of lead and tin by the abscissæ, and the temperature by the ordinates. And, again, the diagram has been drawn from results obtained by experiment. The following facts are not based upon reasoning or logic, but are to be accepted because it is known that the different actions described actually took place upon trial.

2. Consider first a solution containing 83 per cent. of lead and at a temperature of 300° C. This will be represented by the point *a* in Fig. 241, and will be a solution of lead in tin, still liquid,

although about 26° below the melting-point of lead itself. If cooled, the solution will remain liquid until it reaches a temperature of about 275°, which brings it, we see, to the line *A B*. This is the lowest temperature to which it will go and retain that much lead in solution. If cooled any more, the lead will begin to precipitate and of course as much as is precipitated will immediately solidify, being already well below its melting-point. The lead comes out as crystals of solid lead, which remain mixed with the mass of the molten solution, but form no longer a part of it chemically.[1] The solution, *i.e.*, the part still liquid, becomes enriched in tin in proportion as the lead precipitates. Leaving this alloy here for the moment, let us next consider one with less lead.

3. Now take an alloy with 67 per cent. of lead and 33 per cent. of tin at a temperature of 250° C. This will be represented by the point *b* in Fig. 241. We have again liquid lead dissolved in liquid tin, although the alloy is 76° below the melting-point of pure lead. Suppose this alloy cools until it reaches a temperature of about 240° C., where it meets the line *A B*. It will not cool below that temperature and retain all the lead in solution. If we cool it a few degrees, lead separates out and becomes mechanically mixed with the liquid solution.

4. Consider next an alloy of 55 per cent. lead dissolved in 45 per cent. of tin at a temperature of 250° C. As this cools to a temperature slightly below 225°, it again meets the line *A B* and crystals of lead separate out and solidify. And so on: any solution, when it cools to a temperature where it meets the line *A B*, reaches its limit of solubility; it cannot cool more and retain all of the lead in solution; but if it does cool, then some of the lead must be precipitated.[2]

5. To sum up the preceding paragraphs, we may then say that the less lead we have in solution (within limits to be afterward defined) the lower the temperature can go without any of it being precipitated. Or, in other words, the less the lead in solution the lower the temperature will go before any freezing begins. This knowledge is the result of experiment, and it has been shown that

[1] It is a fact that when the lead is precipitated from the solution, it carries with it a few traces of dissolved tin, but for the present we neglect this slight impurity for the sake of simplicity, and consider that pure lead separates.

[2] Any lead that is precipitated must of course freeze, because the temperature is already below the freezing-point of lead. Conversely, any lead that freezes must be precipitated from the alloy, because we know as a matter of experiment that frozen lead will not retain tin in solution (omitting, of course, the few traces of tin retained by the lead and which, for the sake of simplicity, we omit in the discussion).

the line $A\ B$ in Fig. 241 represents the equilibrium between the amounts of lead in the different solutions and the temperature to which each will cool before any lead is precipitated, or, in other words, the amount of lead that saturates the solution at each temperature.

6. With this knowledge let us consider again the first solution —containing 83 per cent. of lead. We have stated that when this solution was cooled below 275° C., some lead was precipitated. Have we any evidence now as to how much lead would be precipitated with each unit drop in temperature? Evidently we have, for we know how much lead is normally in the saturated solution at each temperature; this evidence is given to us by the line $A\ B$. For example, assume that the solution containing 83 per cent. of lead is cooled to 240° C.; how much lead will be left in solution, and therefore how much will have been precipitated? From paragraph 3 we know that 67 per cent. of lead remained in solution down to a temperature of 240° C. and that there was an equilibrium between the amount of lead and this temperature, or, in other words, the solution is saturated with lead at this point. Therefore it would be reasonable to suppose that the solution which started with 83 per cent. of lead would retain exactly 67 per cent. of lead by the time the temperature of 240° is reached. That this reasoning is correct is proved by experimental evidence.

7. Now let us cool the same alloy to a temperature of 225°; how much lead will this retain in solution and how much would be in a precipitated form? We have already seen (paragraph 4) that an alloy containing 55 per cent. of lead will retain all of that lead in solution until it falls to a temperature of 225°. Therefore it is reasonable to suppose that the cooling alloy we are considering will retain just 55 per cent. of lead and no more by the time its temperature has fallen to 225°, and this is in fact the case. In short, each so ution will always retain enough lead to keep it in a saturated state after it once becomes saturated.

8. We have learned above that every point on the line $A\ B$ represents the maximum amount of lead that can be retained in one of these solutions at that temperature. Therefore as soon as any solution meets the line $A\ B$, it follows along this line as it cools and lead precipitates in amounts proportional to the temperature, so that the solutions will always be saturated with lead.

9. It is therefore evident that if we start with any of these liquid alloys containing an amount of lead represented on the

diagram to the left of the point *B*, lead will precipitate from it during cooling and the amount of lead in solution will continually decrease, so that the composition of the alloy at the different temperatures will be represented by a point traveling down the line *A B*. Therefore, in every such case we shall reach finally a solution with 31 per cent. of lead and 69 per cent. of tin (the proportions represented by the abscissa of the point *B*) when the temperature has fallen to 180° C. (the ordinate of the point *B*). Mixed with the solution at this temperature will be the amount of lead which has separated during cooling and which will depend upon the percentage in the original solution. (If this is not clear on the first reading, a little thought will make it so, especially if the reader follows in Fig. 241 each action I have described, step by step.)

10. We have considered up to now only the solutions containing large amounts of lead and from which lead is precipitated on cooling. Let us now consider a solution containing 90 per cent. of tin at a temperature of 225° C. (point *d*, Fig. 241). It is still liquid, although below the normal melting temperature of both lead and tin. This will cool until a temperature of about 210° is reached and it meets the line *C B*. If it cools any more, tin will be precipitated and will of course freeze, because it is already below its normal freezing-point (231° C.).

11. Consider next an alloy containing 85 per cent. of tin at a temperature of 225° (point *e* in Fig. 241). This will cool to about 200° C., where it meets the line *C B*, but if it cools any further, tin will be precipitated and will freeze.

12. In other words, the line *C B* represents the conditions of equilibrium between the temperature and the amount of tin that will be retained in solution, just as the line *A B* represented the equilibrium between the temperature and the amount of lead that would be retained in solution. That is to say, every point on the line *C B* represents the amount of tin that will saturate a solution at that temperature.

13. Returning then again to the alloy containing 90 per cent. of tin, how much tin will have been precipitated by the time the alloy cools to, let us say, 200° C.? Obviously 5 per cent. of tin would have been precipitated, leaving a solution containing 85 per cent. of tin, because we have already seen that 85 per cent. of tin will saturate a solution at 200° C.

14. Whatever solution we may have had to start with, pro-

vided there was always more than 69 per cent. of tin, as soon as that solution met the line *C B* it would travel down this line, precipitating tin progressively in proportionate amounts such that the tin left in the solution at the varying temperatures would correspond to the ordinates of the line *C B*. In other words, this solution follows the line *C B*. Therefore, in all such alloys we shall finally arrive at a solution having 31 per cent. of lead and 69 per cent. of tin (the abscissa of the point *B*) when the temperature has fallen to 180° C. This solution is known as the "eutectic" solution, and with it will be mixed precipitated tin in amount depending upon the amount of tin in the original solution.

15. We may now sum up paragraphs 9 and 14 by saying that whatever solution of lead and tin we have to start with, we will always have one containing 31 per cent. of lead and 69 per cent. of tin by the time the temperature has fallen to 180°, and with this solution will be mixed some precipitated tin or precipitated lead, as the case may be (unless, of course, we started with exactly 31 per cent. of lead and 69 per cent. of tin).

Now let us consider the further cooling of these alloys. What will happen, however, to the solution containing 31 per cent. of lead and 69 per cent. of tin, which we have called the "eutectic" solution? It is evident that when this solution cools below 180°, it must cross the point *B*, and therefore both the lines *A B* and *B C* at once. Obviously, it cannot cross either of these lines without precipitating lead or tin. In point of fact, on crossing both of the lines at the same time, it precipitates at once all the remaining lead and all the remaining tin, and therefore completes the decomposition of the solution and the solidification.

The lead and tin separate in tiny solid crystals or flakelets, which arrange themselves in a parallel banded structure similar to that shown in Fig. 251, page 294. This structure is known as the "eutectic" structure. The term "eutectic alloy" means etymologically "well-melting alloy," because it remains melted longer than any other alloy of the same metals, and every solution, the components of which are soluble in each other in the liquid state and insoluble in the solid state, will form a eutectic solution in the way I have described. This applies not only to solutions of metals in each other, but to solutions of metals in liquids which are afterward frozen, and even of salts in water, etc.

Freezing-point Curves.—The lines *A B* and *C B* are often spoken of as the "upper freezing-point curves" of the alloys, be-

cause any alloy which cools to this line will then commence to freeze. The line *D E* is often called the "lower freezing-point curve," because this line represents the temperature of freezing of the eutectic of the series, and we have already shown that every alloy in the series automatically forms a eutectic by "selective" precipitation; therefore every alloy in the series will not be entirely solid until it reaches the temperature at which the eutectic solidifies,[1] which is always the same.

Cooling Curves.—There are certain thermal changes which accompany the chemical changes I have outlined in the preceding paragraphs. These thermal changes are of importance, because it is by means of them that we are usually able to obtain the first evidence of the precipitation of excess metal, the formation and solidification of a eutectic, etc. Consider the alloy containing 83 per cent. of lead and 17 per cent. of tin, at 300° C., and let us observe by means of a thermometer or pyrometer the rate of cooling. At first the thermometer will fall pretty fast, but when we reach 275°, where the line *A B* is met, the rate of fall is suddenly retarded. It thus becomes evident to us that some event counteracts the fall in temperature. What this event is we learn from microscopic evidence, and, as has already been explained, it is the precipitation of lead. This explanation might have been expected, because the precipitation of lead at a temperature below its normal freezing-point would of course be accompanied by freezing and, during the freezing, the metal would liberate its latent heat of fusion and thus oppose the cooling of the mass as a whole. The rate of fall of temperature is, moreover, retarded all the way down to 180°, because lead is being continuously precipitated as the solution travels down the line *A B*. When we reach 180°, the fall of temperature is not only retarded, but actually ceases; in some cases the temperature may rise slightly. This change is due to the large amount of latent heat of fusion liberated by the rapid freezing of the eutectic at one temperature. This arrest continues until the eutectic is entirely solid, after which the rate of fall becomes rapid again and proceeds without important change until the atmospheric temperature is reached, because now we have nearly the cooling of a solid alloy.

These changes are represented diagrammatically in Fig. 242, in which the abscissæ show the time, in minutes, from the begin-

[1] Some metallurgists prefer not to draw the line *DE*, but to represent the freezing of the eutectic merely by the point *B*.

ning of the cooling, and the ordinates show temperatures. The change in direction at the point *a* shows the retardation due to the precipitation of the lead, while the long horizontal part at *b* shows that for several minutes the temperature was not falling at all, because the eutectic was freezing.

Next, experimenting upon the alloy with 67 per cent. of lead, we find that it cools rapidly until it meets the line *A B*, when the rate of fall is retarded continuously until we reach 180°, where again an arrest (or perhaps an actual rise) of the temperature is observed, after the completion of which the fall in temperature becomes rapid again and proceeds normally.

Similar thermal changes are observed in the alloy containing 55 per cent. of lead, but at temperatures of 225° and 180°. Now,

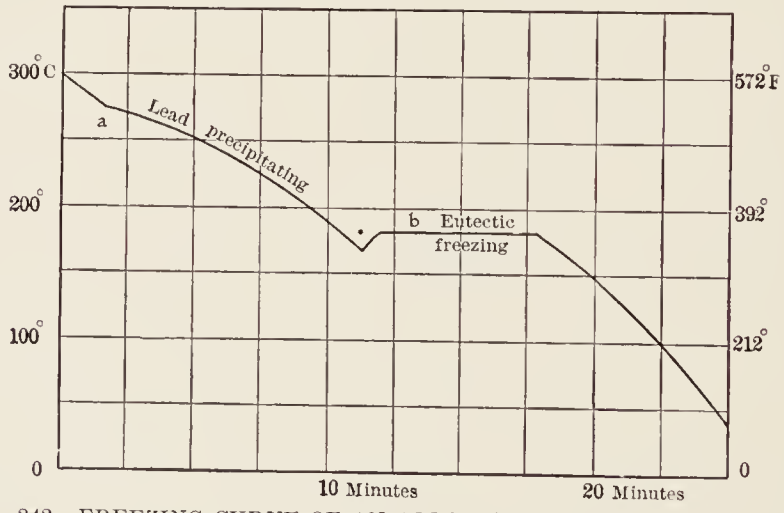


FIG. 242.—FREEZING CURVE OF AN ALLOY CONTAINING 83 PER CENT. OF LEAD AND 17 PER CENT. OF TIN.

by plotting the upper changes in the several solutions (*i.e.*, at 275° C., at 240° C., and at 225° C.), the position of the line *A B* is determined, and by plotting the lower changes (*i.e.*, at 180° C. in each case) the line *D E* is determined.

In studying the solutions of the series rich in tin, similar thermal changes are observed. Consider the alloy containing 90 per cent. of tin and 10 per cent. of lead; this will cool rapidly until a temperature of 210° C. is reached, when a retardation will occur and will persist until the temperature 180° is reached. By this time the excess tin will all have been precipitated and the residual solution[1] will have travelled down the line *C B* to the

[1] These residual solutions are technically known as "mother liquors" or "mother metals," because it is out of them that the solid metal is being "born."

point *B*. Thereupon an arrest (or an actual reversal) in the rate of cooling will occur until the eutectic has solidified, after which the cooling will proceed at a rapid rate. In the case of the alloy containing 85 per cent. of tin, the first retardation will begin at 200°, and then an arrest at 180°. By plotting the points at 210° and 200°, we obtain the position of the line *C B*,[1] and by plotting the two points at 180° we obtain further points to determine the line *D E*.

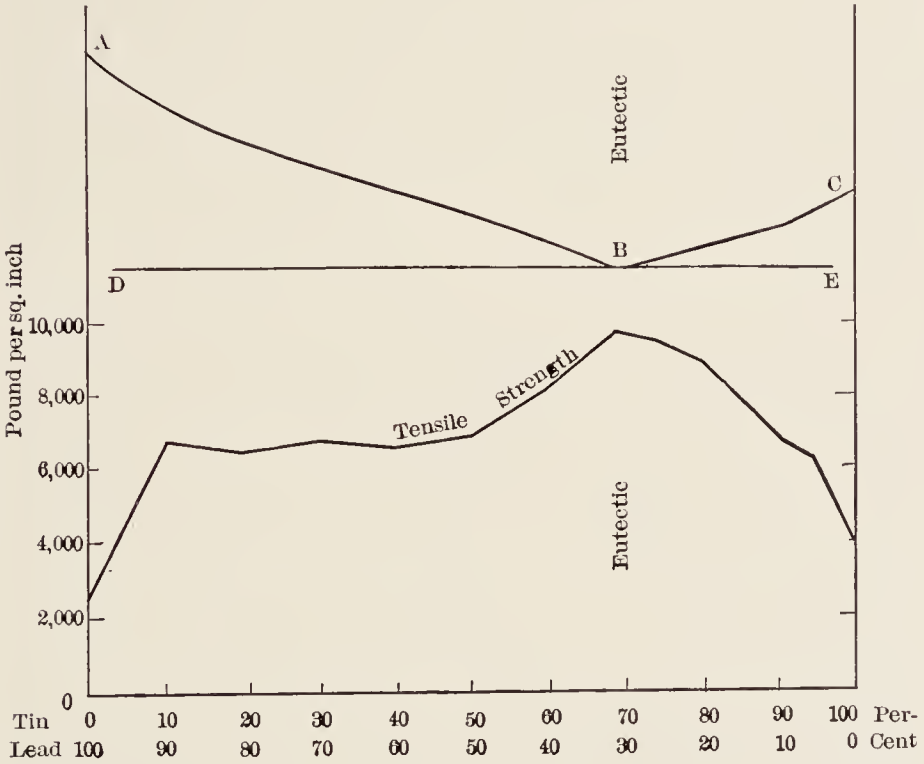


FIG. 243.—FREEZING-POINT AND STRENGTH CURVE OF THE LEAD-TIN ALLOYS.

Properties of Eutectics.—As already said, not only the lead-tin alloys, but every alloy of which the components are soluble when liquid, and insoluble (or nearly so) when solid, will form eutectics, and it happens that this is the case with the great majority of our metallic alloys. For this reason the properties of the eutectic are very important in all metallurgical work. It will be seen that a eutectic is not a chemical compound in atomic proportions. For example, in the case of the lead-tin alloys, the point *B*

[1] It should be understood that in actual experimental determination of lines corresponding to *AB*, *CB* and *DE*, in any series of alloys, not a few, but a large number of different solutions are studied, and a great many retardation points are found before the lines are drawn.

comes at 31 per cent. of lead and 69 per cent. of tin merely because the line *A B* crosses the line *C B* at this ordinate, and this has no relation to atomic ratios. If the melting-point of tin happened to be higher, or if it did not precipitate from lead so fast upon cooling, the line *C B* would cut the line *A B* at a different point, and therefore the composition of the eutectic would be different.

The structure of the eutectic is also very important. The majority of eutectics have a structure similar to the banded form shown in Fig. 251. The tiny crystals in this structure are intermingled very intimately, and this close association has a beneficial effect on the strength of the mixture. In Fig. 243 we may see how the curve showing tensile strength rises to a maximum at the point corresponding to the eutectic of the series of lead-tin alloys.

The Freezing of Iron and Steel

1. When the iron and steel alloys are liquid, they are composed of liquid carbon dissolved in liquid iron, and their freezing-point curves are shown in Fig. 244, p. 287. It will be noticed that the lines in this figure bear a close similarity to those in Fig. 241. This similarity is real, and the laws governing the freezing of this series of alloys are very similar to those governing the freezing of the lead-tin alloys. There is a eutectic of this series when the line *A B* crosses the line *C B*, and the components of this eutectic are 95.7 per cent. iron and 4.3 per cent. carbon. In the study of the iron-carbon alloys, however, we have to take into account a solid solution which forms. That is to say, we must remember that iron, if it contains as much at 2.2 per cent. of carbon, never separates from the liquid state without carrying 2.2 per cent. of carbon with it in solid solution.[1] It will be remembered that when lead separated from the liquid solution, it carried with it a small amount of tin as an impurity, and that when tin separated, it carried with it a small amount of lead as an impurity; but we disregarded these traces of impurity for the sake of simplicity in outlining the laws of solutions. In the case of iron-carbon alloys, however, the carbon carried out with the iron in solid solution,

[1] This solid solution may consist of carbon dissolved in the iron, or of iron carbide dissolved in the iron. We do not know definitely which, but it is not necessary to discuss this question just yet. If it contains less than 2.2 per cent. carbon, it retains all of it in solid solution.

substantially as an impurity, is too important in its effect upon the material to permit us to neglect it.

2. The line $X\ Y$ therefore divides the diagram in Fig. 244 into two parts. Everything to the left of this line freezes as a solid solution and the laws are similar to the freezing laws of the gold-

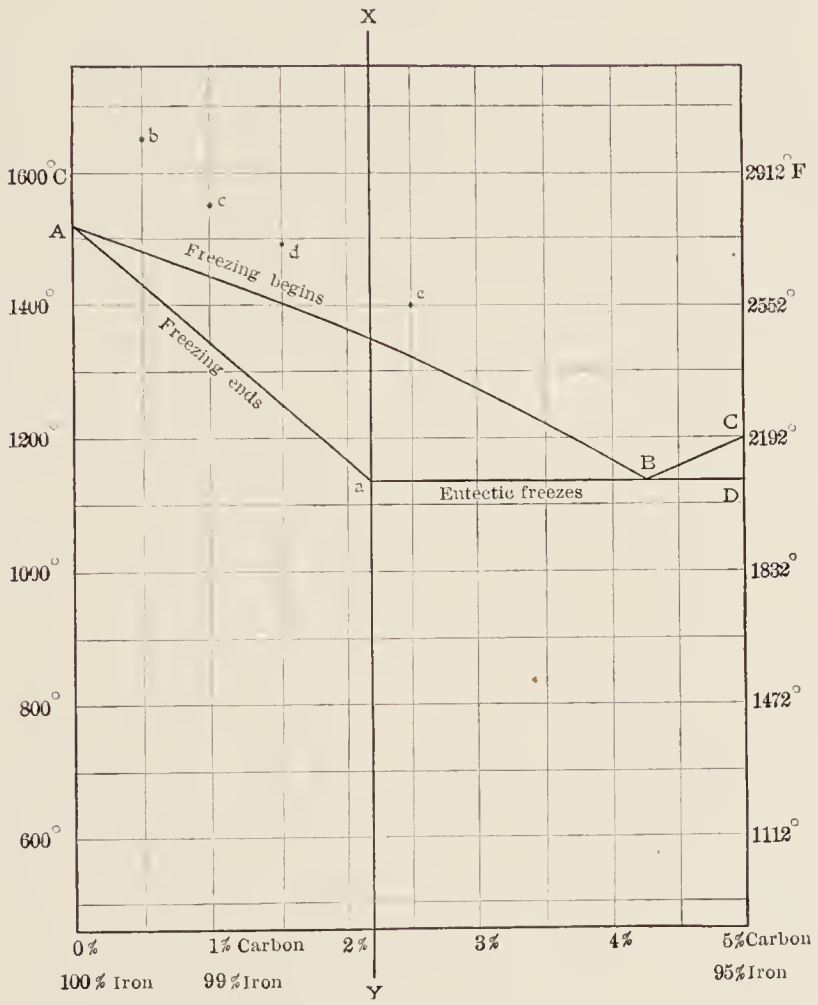


FIG. 244.—THE FREEZING OF ALLOYS OF IRON AND CARBON.

silver alloys. Everything to the right of the line $X\ Y$ freezes selectively, according to the same laws as those given in the case of the lead-tin alloys. It is because of this difference in the freezing of the alloys that the line $X\ Y$ is arbitrarily considered as the dividing line between steel and cast iron. That is to say, all the alloys with less than 2.2 per cent. carbon are defined as steel, and all with more than 2.2 per cent. carbon are defined as cast iron.

3. *Freezing of Steel.*—All the steels freeze as solid solutions. Let us consider a solution of 99.5 per cent. iron and 0.5 per cent. carbon at 1650° C. This will be represented by the point *b* in Fig. 244. This cools until it meets the line *A B*, and now it commences to solidify. For a few degrees of temperature it is part liquid and part solid, but by the time it has fallen to a temperature where it meets the line *A a*, it has become entirely solid, and it is now a homogeneous solution of 0.5 per cent. of carbon in iron. Consider next a solution containing 99 per cent. of iron and 1 per cent. of carbon, at the point *c* in Fig. 244. When this cools to the temperature where it crosses the line *A B* it commences to solidify and it is in a partly liquid and partly solid condition until it crosses the line *A a*, upon which solidification is completed and it now becomes a homogeneous solution of 1 per cent. carbon in iron. The same actions take place with an alloy containing 98.5 per cent. iron and 1.5 per cent. carbon (the point *d* in Fig. 244), and also in the case of 98 per cent. iron and 2 per cent. carbon. In all these alloys we finally arrive at a solid solution of carbon in iron.[1] To this solid solution the name of "austenite" is given, and this name applies no matter how much or how little carbon is in solid solution. In other words, all steels are in the condition of austenite as soon as their solidification is complete.

4. *Freezing of Cast Iron.*—The freezing of cast iron is shown by the diagram to the right of the line *X Y*, and if we should consider this part as a separate diagram, then it would be similar to Fig. 241, the freezing of the lead-tin alloys. There is one difference to be borne in mind, however: along the line *A B* in Fig. 241 we had a selective precipitation of lead; along the line *A B* in Fig. 244 we have a selective precipitation, not of pure iron, but of iron containing 2.2 per cent. of carbon. In other words, this entity, consisting of a solid solution of iron with 2.2 per cent. of carbon, behaves as if it were an elemental substance. It is sometimes called "2.2 per cent. austenite." Suppose we have, for example, a liquid solution of 2.5 per cent. of carbon in iron at a temperature of 1400° C. This will be represented by the point *e* in Fig. 244. The liquid solution will cool until it reaches a temperature of about 1320° C. At this point there will begin to precipitate the entity of which I have spoken, namely, iron containing 2.2 per

[1] The formation of the solid solution from the liquid solution is discussed in detail in Professor Howe's "Iron, Steel and Other Alloys," but it requires too much space to be discussed here. For our purpose it is sufficient to know that when freezing is completed, we have a homogeneous solid solution of all of the carbon in all of the iron.

cent. carbon in solution. This precipitation will cause the liquid solution to be impoverished in iron, and it will therefore move to the right in the diagram as the temperature falls; or, in other words, it will travel down the line *A B*. By the time the temperature of 1135° C. is reached, a large amount of 2.2 per cent. austenite will have precipitated, and the small amount of liquid solution left will be at the point *B*, that is, the eutectic point, where there is 4.3 per cent. carbon. With further cooling the eutectic will cross the point *B*, and therefore will complete its precipitation and its freezing. It decomposes into crystals, a part of which are of tiny flakelets of the austenite before mentioned and the other part, crystals of graphite—*i.e.*, carbon.

5. A similar result will be obtained in the case of a 3 per cent. liquid solution of carbon in iron. This will cool until it reaches 1280° C., where the 2.2 per cent. austenite will precipitate, decreasing the residual solution in iron so that it travels down the line *A B* and finally reaches the point *B*, after which this eutectic solution at the point *B* will precipitate as before.

6. We may sum up paragraphs 4 and 5 by saying that any solution of iron containing more than 2.2 per cent. and less than 4.3 per cent. of carbon will consist, after freezing, of a eutectic together with a certain amount of previously precipitated austenite (consisting of iron with 2.2 per cent. of carbon in solid solution).

7. What will occur in case the solution contains more than 4.3 per cent. of carbon?[1] Take, for example, a liquid solution containing 4.7 per cent. of carbon at a temperature of 1200° C. This will cool until a temperature of about 1170° is reached and the line *C B* is met. As cooling proceeds to lower temperatures, carbon (*i.e.*, graphite) precipitates out and the liquid solution remaining moves to the left in the diagram. That is to say, it travels down the line *C B*. When the temperature 1135° is reached, so much graphite is precipitated that the residual solution is now of the eutectic proportions. With further cooling, this eutectic breaks up as before, consisting thereafter of crystals of graphite and of austenite with 2.2 per cent. of carbon.

8. *Summary.*—To sum up, then, all the solutions of iron and carbon containing less than 2.2 per cent. of carbon will consist, after solidification, of a solid solution of iron and carbon having

[1] It is very seldom that solutions contain more than 4.3 per cent. of carbon, because this much carbon does not readily dissolve in iron,

the same chemical composition as the original liquid solution, and being a homogeneous solution of one in the other. There can be no eutectic form if there is not more than 2.2 per cent. carbon. All the solutions with more than 2.2 per cent. of carbon will consist, after solidification, of a eutectic together with a certain amount of previously precipitated graphite or of the previously precipitated 2.2 per cent. austenite mentioned.

Changes on Heating.—In the foregoing discussion we have been considering only the changes that occur during the cooling of the metal. These changes are simply reversed on heating.

We have seen that every alloy of iron and carbon contains, after solidification, a varying amount of the solid solution of iron and carbon. For example, if we started with 1 per cent. of carbon, then, immediately after solidification, we would have a solid solution of 1 per cent. carbon in iron; if we started with 1.5 per cent. of carbon, we would have a solid solution containing 1.5 per cent.; if we started with 2.2 per cent. of carbon, then we would have a solid solution of 2.2 per cent. carbon. Even if we start with more than 2.2 per cent. carbon, then the alloy, after solidification, will consist partly of a solid solution containing 2.2 per cent. of carbon and partly of graphite.

Now, what becomes of these solid solutions which make up a part or a whole of the cast iron and steel alloys when they freeze? Does the carbon remain in solid solution down to the atmospheric temperature, or does it precipitate, or does it undergo some other change? We find by experiment that the solid solutions do not survive, but precipitate at a lower temperature, and the laws governing the decomposition of these solid solutions are similar to the laws governing the decomposition of liquid solutions—for example, the lead-tin solutions. In short, we have another series of curves showing the selective precipitation of the constitutents of these solid solutions, and the only difference between the nature of these curves and the lead-tin curves is that these represent changes taking place in the solid state, while the lead-tin curves represent changes taking place in the liquid state.

Nature of the Solid Solution.—In the footnote on page 286 I called attention to the fact that the solid solution of iron and carbon might be a solution of pure carbon in iron, or a solution of a carbide of iron in iron, for example, of Fe_3C in iron. Several authorities hold this view,[1] while other maintain that the solution

[1] Indeed, one authority believes that there are probably several different carbides (Fe_3C, Fe_2C, FeC) dissolved in the iron.

is of elemental carbon in iron. The question is of more academic than practical interest. The important thing is that, when the solution decomposes, it is a carbide of iron which precipitates. Those who believe that the solid solution is composed of elemental carbon and iron explain the precipitation of the carbide by main-

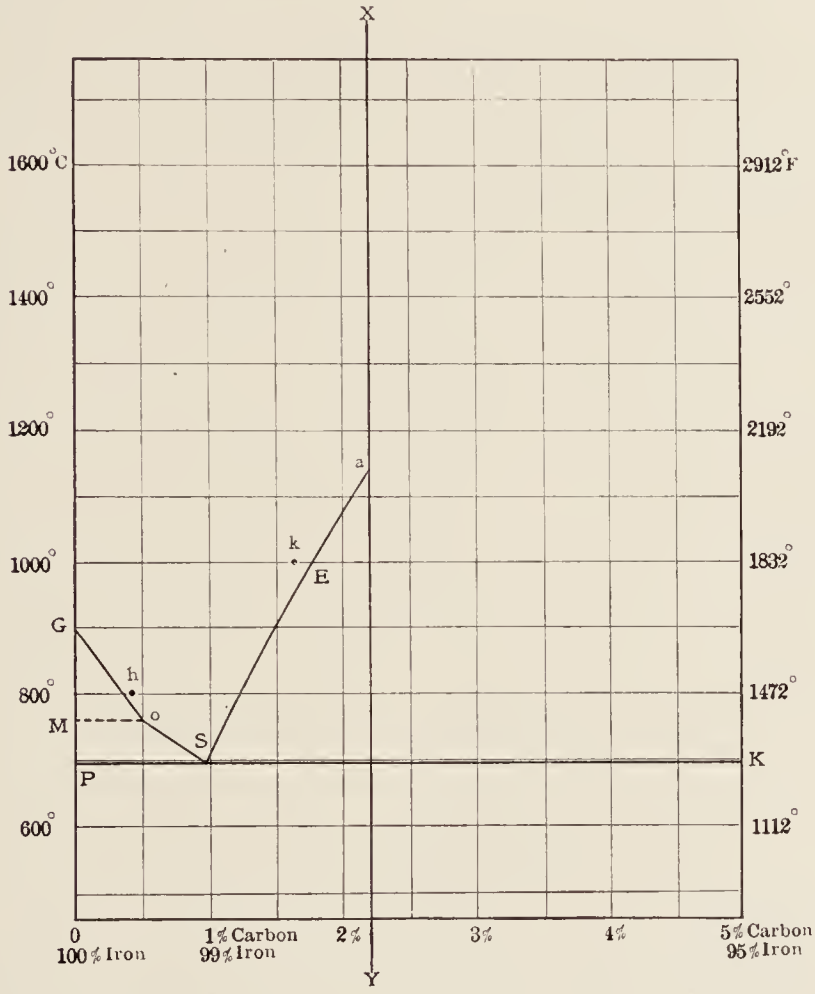


FIG. 245.—DECOMPOSITION CURVES OF THE SOLID SOLUTIONS OF IRON AND STEEL. (ALSO KNOWN AS THE CRITICAL POINTS.)

taining that when the carbon separates from solution, it immediately unites with iron and forms a carbide, usully Fe_3C. With this explanation I shall hereafter, for simplicity's sake, discuss the solid solutions as if they were Fe_3C in iron.

The Decomposition of the Solid Solutions.—The curves of decomposition of the solid solutions are shown in Fig. 245. The line *G O S* is the line upon which there is selective precipitation of pure

iron. To this pure iron the name of "ferrite" has been given by Professor Howe, and this name meets with universal acceptance.

Consider first a solid solution containing 0.40 per cent. of carbon at a temperature of 800° C. This will be at the point *h* in Fig. 245. It will cool until it reaches a temperature of about 780° C. upon which ferrite will begin to precipitate. As the temperature continues to fall more and more ferrite precipitates, which impoverishes the solid solution in iron and causes it to travel down the line *O S*. By the time the temperature has reached 690°, the solid solution has reached the point *S*, corresponding to 0.90 per cent. carbon.

Consider next an alloy containing 1.60 per cent. carbon at 1000° C.: this will be at the point *k*. It will cool until it reaches a temperature of about 970°, at which carbide of iron (Fe_3C) will begin to precipitate. This precipitation continues as the temperature falls, constantly decreasing the amount of carbon in the solid solution, which therefore travels down the line *E S* until, at 690°, it reaches the point *S*, where there is 0.90 per cent. carbon.

A similar precipitation will take place with all of the solid solutions of iron and carbon: if they contain less than 0.90 per cent. carbon, they will begin to precipitate out ferrite when they fall to the line *G O S*. If they contain more than 0.90 per cent. carbon, they will begin to precipitate carbide of iron when they meet the line *E S*. In either case the residual solid solution will travel down the line *G O S*, or else *E S*, until it reaches the point *S* when the temperature has fallen to 690° C.; we will then have some solid solution left containing 0.90 per cent. carbon, and mixed with this some previously precipitated ferrite or cementite, as the case may be.

Eutectoid.—The alloy containing 0.90 per cent. carbon is known as the "eutectoid alloy," a name invented by Professor Howe to indicate that the formation of this alloy, which results by selective precipitation of the solid solution, is similar to the formation of the well-known eutectics of liquid solutions. When this eutectoid solid solution cools below 690° C., it is completely decomposed into its constituents, ferrite and cementite. These constituents precipitate in tiny flakelets, which arrange themselves in the banded structure already familiar to us as the structure of eutectics. A magnified view of the structure is shown in Fig. 247, while Fig. 248 shows the magnified structure

of a piece of steel composed of a eutectoid together with previously precipitated ferrite; and Fig. 249 shows the structure of a steel consisting of the eutectoid with previously precipitated cementite.

It will be evident that there will be some of the eutectoid in every piece of iron or steel, for even the cast irons contain, after solidification, a certain amount of solid solution which precipitated either while the liquid alloy was traveling down the line *A B*, or during the freezing of the liquid eutectic (containing 4.3 per cent. of carbon), or both. The formation and characteristic of this eutectoid are therefore of very great importance. Its presence in iron and steel was known long before the theories that I have outlined in this chapter had begun to be understood, and the name of "pearlite" was given to it because, under certain circumstances, it has the appearance of mother-of-pearl. The name pearlite is only used to designate the eutectoid after its complete decomposition and the separation of the ferrite and cementite into the banded structure shown in Fig. 250.

Changes on Heating.—As in the case of the liquid solutions, the changes already described above in connection with the cooling of the solid solutions are reversed on heating. The temperatures at which the reverse changes occur on heating, however, are somewhat higher than the corresponding change on cooling, unless both cooling and heating be very slow. In other words, the chemical changes seem to lag behind the temperature changes. With extremely slow heating and cooling, the lag is but slightly perceptible, and the various changes and reversals take place at almost the same temperature, but with the rates of cooling usually employed in research laboratories at steel works, there is a difference of about 20° between the temperatures of the changes in the different directions. It is customary to plot the curves as in Figs. 241, 244, showing temperatures on cooling, and that method has been adopted here.

The Complete Roberts-Austen, Roozeboom Diagram

We may now take the diagrams of Figs. 244 and 245 and combine them into one diagram which shall represent *all these changes* in the heating and cooling of iron and steel. Such a diagram is shown in Fig. 252. Nevertheless, this diagram does not by any means tell the whole story; there are many changes

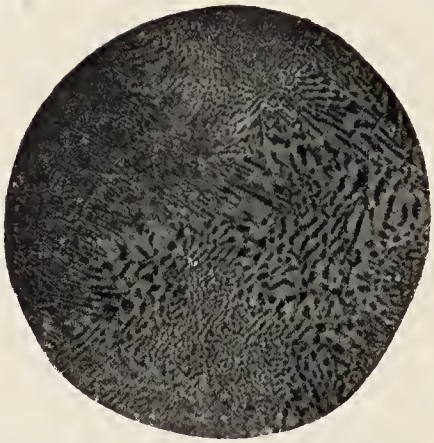


FIG. 246.—EUTECTIC OF COPPER AND SILVER.
(William Campbell.)

FIG. 247.—PEARLITE EUTECTOID OF IRON AND CARBON.
(F. Osmond.)

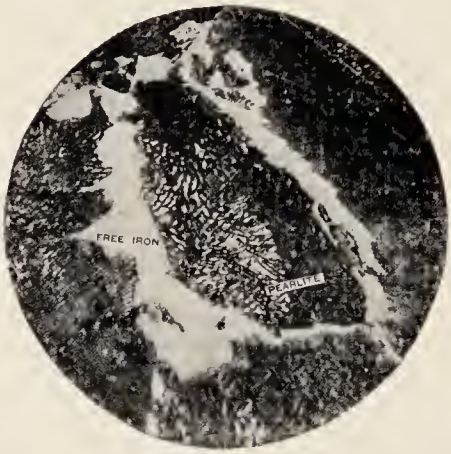


FIG. 248.—PEARLITE AND FERRITE.
250 diameters.

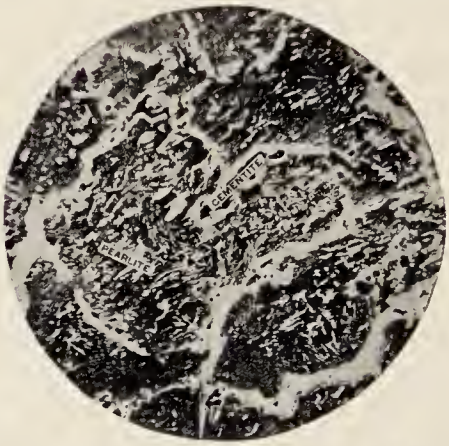


FIG. 249.—PEARLITE AND CEMENTITE.
250 diameters.

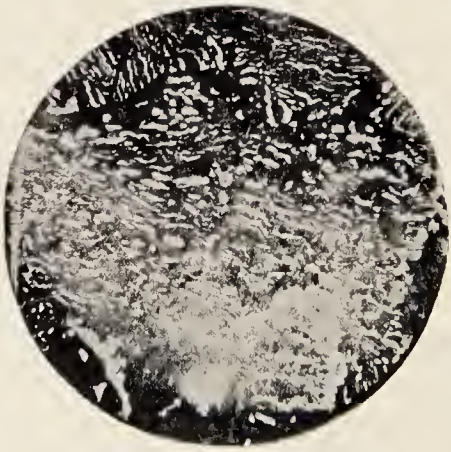


FIG. 250.—PEARLITE.
250 diameters.

FIG. 251.—PEARLITE.
1000 diameters.

Picric Acid.—Large crystallization due to long overheating. Polished in Relief.

whose nature is not yet understood, but evidence of which is conclusive. We must leave most of these to treatises devoted to this special branch of iron and steel metallurgy, on account of lack of space here, but one important modification must be included because of its great usefulness in controlling the properties of cast iron; this modification is the effect of silicon on the changes occurring in freezing.

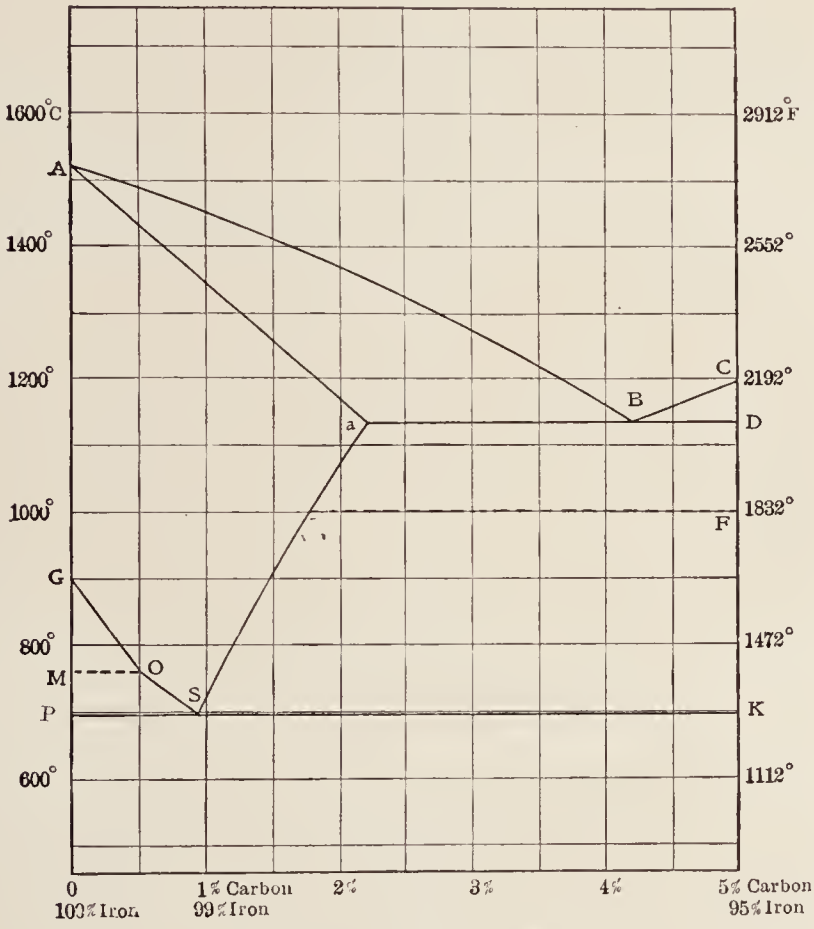


FIG. 252.—THE FREEZING AND SOLID DECOMPOSITION CURVES OF THE IRON ALLOYS.

Effect of Silicon on the Freezing of Cast Iron.—The changes shown in Figs. 244 and 252 refer to the freezing of normal gray cast iron used for iron castings and cooled moderately slowly as in the practice of founding, etc. Under such conditions there is a formation of austenite with graphite, the austenite subsequently decomposing into ferrite and iron carbide (*cementite*), as described. Indeed, when there is some 2 per cent. or so of silicon

present as there often is in foundry irons, the austenite decomposes in large part into ferrite and graphite, instead of ferrite and cementite, so that such irons, when cooled to atmospheric temperature, will consist largely of ferrite and graphite, with only a small amount of combined carbon. It is this freedom from much cementite that causes iron castings to machine so readily. In short, silicon tends to produce a precipitation of graphite instead

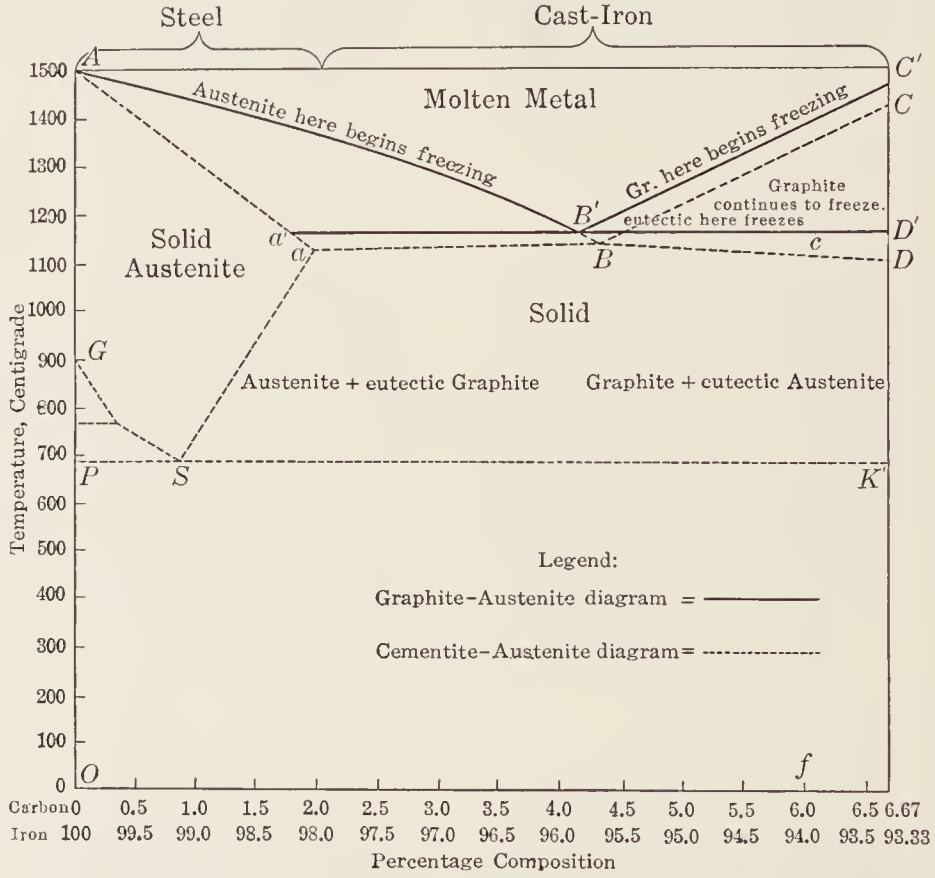


FIG. 253.—THE STABLE AND METASTABLE IRON-CARBON DIAGRAM.

of cementite. This effect of silicon operates not only during the decomposition of the eutectoid, but also during freezing.

In other words, when we experiment in the laboratory with pure iron and carbon, free from silicon and other impurities—a kind of iron, be it noted, that does not exist commercially—the products of freezing are not austenite and graphite, but austenite and cementite. Such an iron, when cooled to atmospheric temperature, will consist of eutectoid plus cementite, and no graphite will be found in it. This result is represented by the

dotted lines of Fig. 253. When cooling pure irons, free from silicon, etc., the product will be according to these dotted lines, and the word cementite should be substituted at every point where graphite occurs. The full lines, on the other hand, represent the action when commercial irons are cooled.

Effect of Rate of Cooling.—None of the changes represented by these diagrams are instantaneously completed. This enables us to control them to a limited extent. For example, in the case of a cast iron (unless the silicon be very high) we can prevent the formation of any graphite by cooling the liquid metal very rapidly, as, for instance, by pouring it into cold water. The result will be that most of the carbon will remain dissolved in the iron as it was in the liquid state, while the remainder will be in the form of cementite. In the case of steel, we may largely prevent the separation of ferrite and cementite from the austenite by cooling the steel rapidly from the temperature where austenite exists, *i.e.*, above the lines *G O S a*.

Other Lines in Fig. 253.—Certain retardations in the cooling curves would indicate that there was a line extending all the way across this dagram at about 775° C., and another at 600° C.

Roberts-Austen.—The diagram of Fig. 252 is often known as the Roberts-Austen diagram, after Sir William Roberts-Austen, because the cooling curves that located the lines were first determined in his laboratory.[1]

Upton's Diagram.—One of the latest theories to help clarify the equilibrium of the iron carbon alloys is that of Upton, and he has collected his hypotheses into the diagram shown in Fig. 254. It will be seen that this diagram involves the acceptance of three different carbides of iron. There are certain suppositions in this diagram which are not correct, but it has gone a long way toward explaining several of the observed phenomena and as such should be familiar to all metallurgists. It does away with the theory of a stable and metastable eutectic, and assumes that the eutectic consists of austenite plus graphite, which solidifies at 1145° C., but that, at about 1095° C. the compound Fe_6C is formed. If there be less than 3.46 per cent. of total carbon present, the formation of this Fe_6C will use up all the graphite and the alloy

[1] See "Proceedings of the Institution of Mechanical Engineers" (England), 1897, Fourth Report of the Alloys Research Committee, Plate 2. See also "Le Fe et l'Acier au Point de Vue de la Doctrine des Phases," H. W. Bakhuis-Roozeboom, in *Zeitschrift für physikalische Chemie*, vol. xxxiv, p. 437: French translation, "Contribution à l'Etude des Alliages," pp. 327–386, Paris, 1901.

will contain only gamma iron and Fe_6C in solution. If there be more than 3.46 per cent. of total carbon present then only the excess of carbon over 3.46 per cent. will appear in the form of graphite.

However, the recombinations of graphite and formation of Fe_6C is a very slow reaction indeed, taking place only to a limited degree in any industrial cooling and being therefore of theoretical rather than of practical application, except that the tendency

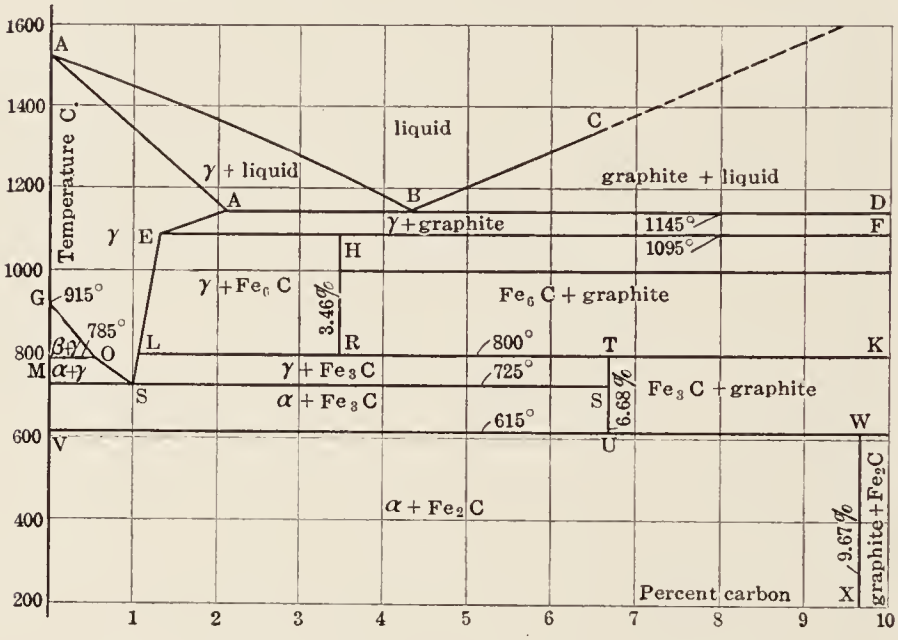


FIG. 254.—UPTON'S DIAGRAM OF THE IRON-CARBON ALLOYS.

for this action to occur explains certain hitherto puzzling reactions, such as for instance, the reabsorption of temper carbon when malleable cast iron is over-annealed.

On further cooling the Fe_6C breaks up, and Fe_3C is formed, which would result in the absorption of more graphite if the cooling were sufficiently slow, but again the extreme slowness of this reaction causes it to take place completely only under such conditions as prevail in the laboratory, as a rule. For further discussion of this very interesting theory, the reader is referred to the original article in the Journal of Physical Chemistry, Vol. XII, No. 7, October, 1908, pp. 507 to 549.

XI

THE CONSTITUTION OF STEEL

The properties of steel depend upon the chemical composition of its constituents as well as upon their size and relation to one another. Enough has been said to show that steel is not a simple homogeneous union of iron with varying proportions of carbon, silicon, manganese, etc.; but is built up of individual crystals somewhat in the same way as crystalline rocks are formed—granite, for example. But while the crystals of granite are generally visible to the naked eye, and its structure may therefore be determined by a more or less cursory examination, the structure of steel is visible only by means of the microscope and after careful polishing, sometimes followed by chemical treatment to differentiate between the various grains. Nevertheless, the structure of steel is of great importance, and in some cases, perhaps, is even more so than the chemical composition.

The Micro-constituents of Steel

In this chapter I shall speak only of slowly cooled steel except where I have indicated the contrary. We have already learned that slowly cooled steel must necessarily contain ferrite and cementite, resulting from the decomposition of the solid solution of iron and carbon. There are also other constituents which are found under the microscope, or separated by chemical analysis, or in both ways. These latter constituents are compounds of iron with various other impurities, such as iron sulphide, iron phosphide, and iron silicide; or of two impurities with each other, such as manganese sulphide.

Ferrite.—Ferrite is theoretically pure iron, and especially iron free from carbon. It is weak as compared with several of the other constituents, having a tensile strength of about 45,000 to 50,000 lb. per sq. in; it is also very soft and ductile, resembling copper in these properties, and has, furthermore, a high degree of malleability. It has a very high electrical conductivity as compared with the other constituents of iron and steel, and

about one-seventh the conductivity of copper and silver, the best conductors known. (Copper and silver are of nearly the same conductivity.) Its magnetic force is the highest of any known substance, its magnetic permeability is high, and its hysteresis low. It crystallizes in the isometric system.

Ferrite is an important constituent of all steels and the predominant one in all the low-carbon steels. The industrial product approaching nearest to pure ferrite is wrought iron, if we disregard the slag, which, being mechanically mixed with the mass, does not appreciably alter its chemical and physical behavior. It is for this reason that wrought iron is so useful where a soft and ductile material is necessary, as in boilers for instance; or where high electrical conductivity is demanded, as in telegraph wire; or a high degree of magnetism, as in the cores of electromagnets. The wrought iron made in Sweden, and known as "Norway iron," is greatly preferred for this latter purpose, on account of its purity.

Under the microscope ferrite may be distinguished from cementite by its softness. If steel containing these two constituent, be polished on damp, rough parchment, or on chamois skin stretched over a soft background (as wood), the ferrite will wear away below the carbide and appear in intaglio. The same effect will be obtained by Osmond's "polish attack."[1] Ferrite is also distinguished from carbide of iron by the fact that, after being subjected to the brief action of certain reagents, such as 2 per cent. nitric acid, or ordinary commercial tincture of iodine, the ferrite is seen in darker grains and the carbide in bright thin plates, unattacked by the reagent. When the two are intimately associated in minute grains, as in pearlite, the carbide appears bright and the ferrite dark, because eaten away below the surface by the reagent.

Allotropic Modifications.—There is one peculiarity of pure iron, or ferrite, which deserves special attention, namely, its ability to assume different allotropic modifications at different temperatures. The nature of allotropism has been explained in Chap. XX). To the allotropic modification of iron the names of "alpha," "beta," and "gamma" have been assigned. The alpha modification, is the one existing at atmospheric temperatures, and it is familiar to all who make or use iron. If this be heated, however, it undergoes a sudden change at about 760° C. (1390° F.). This

[1] See page 447.

change is evidenced by an absorption of heat and the circumstance that the iron loses almost entirely its power to attract a magnet; that is to say, it becomes about as non-magnetic as lead, copper, etc. The change in magnetism is accompanied by a change in electrical conductivity, in specific heat, and in other properties. In short, the iron has changed in many of its properties without undergoing any alteration in chemical composition. This new allotropic modification of iron is known as beta iron.

If, now, beta iron be further heated to a temperature of about 890° C. (1634° F.), it again changes several of its properties and becomes what is known as gamma iron. Gamma iron differs from beta iron, especially in electrical conductivity and in crystalline form. Ferrite crystallizes always in the cubic system, and Osmond[1] and Stead[2] have studied the variations of form assumed by it and by its alloys with carbon. Osmond especially has studied the crystallography of the gamma, beta, and alpha modifications of the pure metal. Gamma iron does not crystallize isomorphously with either beta or alpha iron, which crystallize identically in cubes; but it assumes all the combinations of the cube and octahedron, and, in the latter form would be isomorphous with carbon in the diamond form. Therefore, in the isomorphous mixtures (i.e., solid solutions) of iron and carbon one would expect to find some carbon in the diamond form, which has indeed been accomplished by Osmond. This is used as an argument in favor of the belief that the solid solution is with carbon, not with cementite; for Osmond has shown[3] that cementite does not assume any crystalline form which would be isomorphous with ferrite. Beta and alpha iron do not crystallize isomorphously with either carbon or cementite, which accords with the observed tendency of ferrite to begin to separate from the solid solution at the same temperature at which it changes from gamma to beta.

If ferrite is in the gamma form, and say at 1000° C. (1832° F.), it will undergo upon cooling the reverse of the changes which have already been described. That is to say, at about 890° C. (1634° F.) it will change from gamma to beta iron; at 760° (1390° F.) it will change from beta to alpha iron, in each case receiving again the properties which it had before heating. In other words, the change from one allotrophic form to another is

[1] See No. 110. [2] See No. 181. [3] See No. 181.

a reversible change, taking place in one direction on cooling and in the opposite direction on heating. The change on cooling takes place at a slightly lower temperature than on heating. This is not because it is other than a true reverse action, but because the change in either direction is necessarily slow and lags a little behind the temperature. The amount of this lag will vary directly with the speed of heating and cooling.

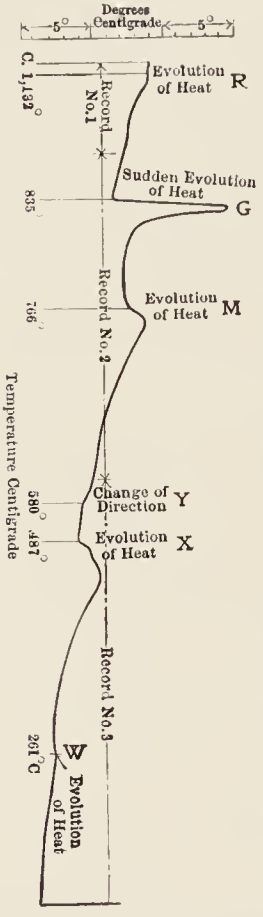


FIG. 260.—COOLING CURVE OF PURE IRON.

We never get pure gamma iron at any temperature unless we start with iron free from carbon, because gamma ferrite never separates from the solid solution. If, however, we have a solid solution of iron with, let us say, 0.2 per cent. of carbon, then this solid solution will begin to precipitate ferrite at a temperature of about 830° C. (1524° F.). This ferrite will be, of course, in the beta form and will be non-magnetic until the mass cools below 760° (1390° F.), when the previously precipitated ferrite will change from the beta to the alpha form. Any ferrite which separates from solid solution after that temperature is reached will separate in the first instance in the alpha form. For example, if we have a solid solution, containing, say, 0.7 per cent. carbon, this will commence to precipitate ferrite below 760° C. (about 720°), and the ferrite will be in the alpha form.[1]

Cementite.—The carbide of iron is, next to ferrite, the most important constituent of steel, and practically all of the carbon is present in this form.[2] Cementite is very hard and brittle, scratching glass with ease and flying into pieces under a blow. It crystallizes usually in thin flat plates, which are large in size (sometimes up to 1/8 in.

[1] Some maintain that the ferrite always precipitates as gamma ferrite, then immediately changes to beta and next to alpha ferrite. Others maintain that when the solid solution is cooled near the line *G O S*, it changes from a solid solution of gamma iron into a solid solution of beta iron, and then into a solid solution of alpha iron, from which alpha iron then precipitates. (See No. 111 and page 378.)

[2] There is not wanting evidence in favor of several carbides being present, such as FeC, Fe_2C, Fe_3C, Fe_6C, etc., but Fe_3C is the one usually considered.

in diameter) when there is much cementite present. It is attacked by reagents less than most of the other constituents and is in this way distinguished under the microscope. It is a little difficult to distinguish, by microscopic evidence alone, between steel consisting of pearlite with a slight excess of cementite and steel consisting of pearlite with a slight excess of ferrite. The practised eye can usually tell; but a chemical analysis readily distinguishes, since steel with less than 0.8 per cent. carbon will have excess ferrite over pearlite, and that with more than 0.9 per cent. will have excess cementite.

Cementite contains 6.6 per cent. of carbon, or roughly, is one-fifteenth carbon. We may therefore tell the amount of cementite in any steel by multiplying the amount of carbon by fifteen.[1] Cementite may be separated from steel by electrolysis.[2] It is magnetic at ordinary temperatures, but not above 700° C. (1292° F.).

The carbon united with iron in cementite has been given various names, such as "cement carbon," or "carbon of cementation" (because of its prominent appearance in cemented steels), and "carbon of the normal carbide," "annealing carbon" (because all the carbon of well-annealed steels will usually be present as cementite).

Manganiferous Cementite.—Manganese forms a carbide having the formula Mn_3C. This is isomorphous with Fe_3C, and we often find the two carbides together in one crystal. The name cementite is still applied to this crystal, although it must be recognized that a part of the iron has been replaced by manganese. The formula for the compound is usually written $(FeMn)_3C$. The amount of manganese in these crystals is very variable, running almost all the way from nothing to 90 per cent. As manganese has an atomic weight almost the same as that of iron (Mn_{55}, Fe_{56}), one weight of manganese will replace almost exactly an equal weight of iron in the crystal. The peculiarity of the manganiferous cementite is that the crystals of free cementite are liable to be larger, especially when the proportion of manganese is large, and are seemingly harder and more difficult to machine.

Manganese Sulphide.—Manganese and sulphur unite to form manganese sulphide, having the formula MnS, and this compound

[1] In other words, steel containing 0.5 per cent. of carbon will contain 7.5 per cent. cementite; steel containing 1 per cent. carbon will contain 15 per cent. cementite; etc.

[2] See No. 112.

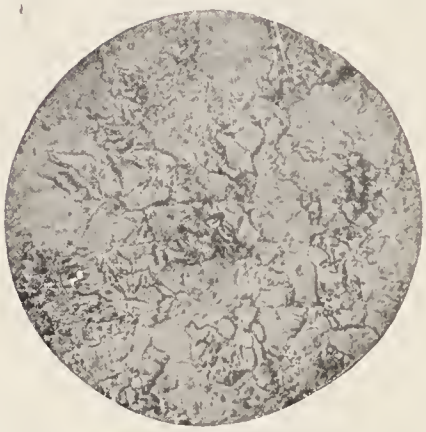


FIG. 261.—FERRITE, PURE IRON (ELECTROLYTIC).
1000 diameters. Etched with picric acid.

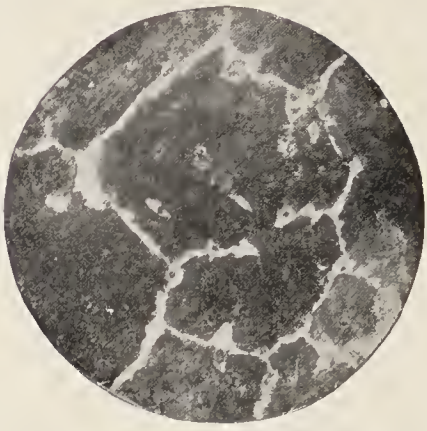


FIG. 262.—PEARLITE CRYSTALS.
Surrounded by ferrite. 250 diameters. Etched with HNO_3.

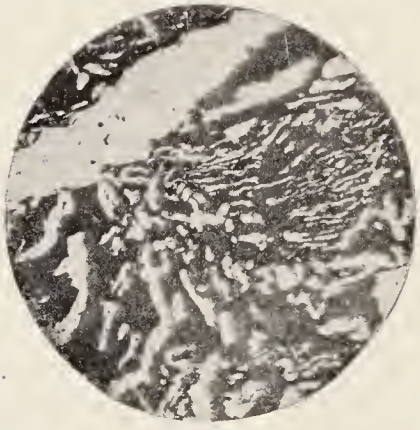


FIG. 263.—BIG CEMENTITE CRYSTAL IN PEARLITE.
250 diameters. Polished in relief.

FIG. 264.—CRYSTALS OF MANGANIFEROUS CEMENTITE.
50 diameters. Etched with nitric acid.

FIG. 265.—ELONGATED BUBBLE OF MANGANESE SULPHIDE.
250 diameters. Unetched.

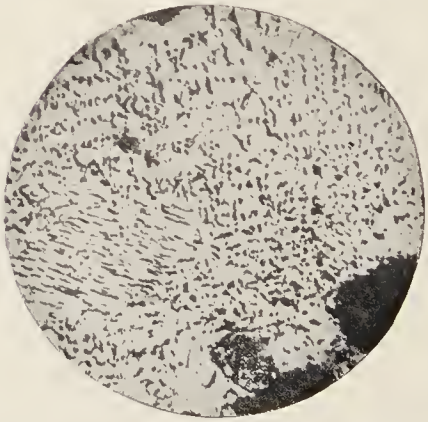


FIG. 266.—EUTECTIC OF Fe_3P AND IRON.
1000 diameters. Etched with picric acid.

is found in all steels. Indeed, all of the sulphur will be found in this combination, provided there is enough manganese in the steel to unite with it. It is necessary to have more than the theoretical amount of manganese for this purpose, however, because unless there is a surplus present, the attraction of the manganese for the sulphur does not seem to be always sufficient to catch it all. Steel should therefore always contain about four times as much manganese as sulphur, because it is advantageous to have the sulphur all in the form of manganese sulphide.

Manganese sulphide is seen under the microscope as a dove-gray substance before the polished material is etched with any reagents. It is usually segregated in round drops, which are sometimes, if large in size, seen to be elongated by the rolling or hammering of the material (see Fig. 265).

Manganese tends to make the crystals of steel smaller, which is advantageous, but makes the metal more liable to crack in heating, and still more so in cooling suddenly from a red heat.

Iron Sulphide.—The bulk of the sulphur not united with the manganese will be found in the form of iron sulphide, FeS. This iron sulphide is more brittle than manganese sulphide, and instead of coalescing in drops, it spreads out in webs or sheets. It is therefore very weakening to the steel, because the area of weakness is more extensive than the tiny spots of manganese sulphide. Steel containing iron sulphide is liable to show poor tensile test and low ductility. It is at the rolling temperature, however, that iron sulphide produces the greatest weakness, because at this point it is in a liquid form and therefore has practically no adhesion to the crystals of steel, which are liable to break along the planes or meshes of sulphide. The same is true, to a less extent, of the effect of manganese sulphide, which is also in a liquid or pasty condition at the rolling temperature; but the extent of its damage is not so great on account of its drawing together in drops.[1] These facts explain the well-known beneficial effect of manganese in counteracting the damage due to sulphur in iron and steel.

Iron Phosphide.—Iron forms at least one phosphide, having the formula Fe_3P, and this phosphide forms with iron a series of alloys, of which the eutectic contains 64 per cent. of Fe_3P (10.2 per cent. of phosphorus). Even 1 per cent. of phosphorus will make the melting-point of iron very much lower, and it is for this

[1] See No. 113.

reason that foundry irons are often desired with a high content of phosphorus. Even where there is a smaller amount of phosphorus there will be some of the phosphorus eutectic formed, and this remains in a molten condition for some time after the bulk of the steel has solidified. This liquid eutectic tends to migrate to the spaces between the crystals, where it remains after solidification and forms a very brittle network, which naturally makes the whole mass more or less brittle. For these reasons phosphorus is the greatest source of brittleness in steel, and especially brittleness under shock, and is thus a great enemy to the engineer and other users of the material.

Besides forming the eutectic, as I have described, phosphorus tends to produce coarse crystallization in steel, and this makes it both weak and brittle. It is a fact observed many times that the embrittling effect of phosphorus on steel is much less when the steel is very low in carbon, and as the carbon rises the brittleness caused by phosphorus rises. This and other effects of phosphorus have been explained by Prof. J. E. Stead in two very able papers.[1] He has shown that a little phosphorus will dissolve in ferrite and that then the eutectic which produces the brittleness will not form, but as the carbon in the steel increases, it precipitates the phosphorus from the ferrite solid solution and therefore causes the eutectic to form. Hence, the more ferrite and the less cementite in steel, the less will be the brittleness produced by phosphorus.

Iron Silicides.—There seem to be three or more silicides of iron, but the one having the formula FeSi seems to be found most commonly in steel. It appears to increase very slightly the strength of steel, and also, to a limited extent, its hardness. The chief importance of silicon, however, as already pointed out, is in promoting soundness.

Iron Oxides.—Oxygen occurs in steel in at least three forms: CO, FeO and Fe_2O_3. In either form its presence is very harmful, producing brittleness in both hot and cold steel, besides causing the liability to blow-holes already discussed. There is probably no constituent more harmful to steel than oxygen, and unfortunately the chemists are far behind in respect of not yet having found a satisfactory method of accurately determining small traces of this gas. The effect of oxygen is somewhat similar to that of sulphur, and, in common parlance, makes the steel "rotten."

[1] See No. 184 and No. 115.

Nitrogen and Hydrogen.—Both nitrogen and hydrogen occur in steel, and one of the theories to explain the superiority of crucible steel is based upon the relative freedom of this material from these two gases. The amount of nitrogen and hydrogen present is usually very small. Hydrogen dissolves very easily in iron at a high temperature, but is evolved in part as the metal cools. In order to obtain entire freedom, however, it is necessary to heat and cool several times in vacuo.

The Strength of Steel

The properties of steel most commonly desired are strength and ductility. Unfortunately there is more or less incompatibility between these two. That is to say, as the strength of steel increases, the ductility usually decreases; and, conversely, as the ductility increases, the strength usually decreases. There are other properties of steel which are likewise of importance, either because they are desired, or the reverse. Among these we shall especially discuss hardness, brittleness, electric conductivity, magnetic permeability, magnetic hysteresis, permanent magnetism and weldability.

Pure iron has a tensile strength of about 45,000 lb. per sq. in. and a compressive strength of about 80,000 lb. per sq. in. These are increased by several of the ordinary impurities found in steel, but the most important strengthener is carbon, because this will increase its strength with the least decrease in ductility.

Carbon.—Each increase in carbon (cementite) gives an increase in tensile strength until we reach a maximum of about 0.9 to 1 per cent. of carbon (13.5 to 15 per cent. cementite). With further increase in cementite there is a decrease in tensile strength. It is probable that the reason for this maximum tensile strength at approximately the eutectoid ratio of the steel is due largely to the small crystallization and the intimate mixture of the crystalline constituents when the steel is at, or near, the eutectoid proportions.[1] With less cementite the grains of pearlite are surrounded by a network of ferrite; with more cementite, the grains of pearlite are surrounded by network of cementite; and both of these networks have a weakening effect upon the material by decreasing the adhesion of the

[1] The still greater increase in strength when the two constituents of the pearlite (ferrite and cementite) are even more intimately associated is explained on page 377.

crystals. The relation between carbon and tensile strength is shown graphically in Fig. 267.

H. H. Campbell and W. R. Webster have studied exhaustively the effect of the different impurities upon the tensile strength of steel. The latest word on this subject has been said by Campbell who gives[1] the following rule for the effect of each 0.01 per cent. of carbon on acid and on basic open-hearth steel. Starting with 40,000 lb. per square inch for pure steel, each 0.01 per cent. of

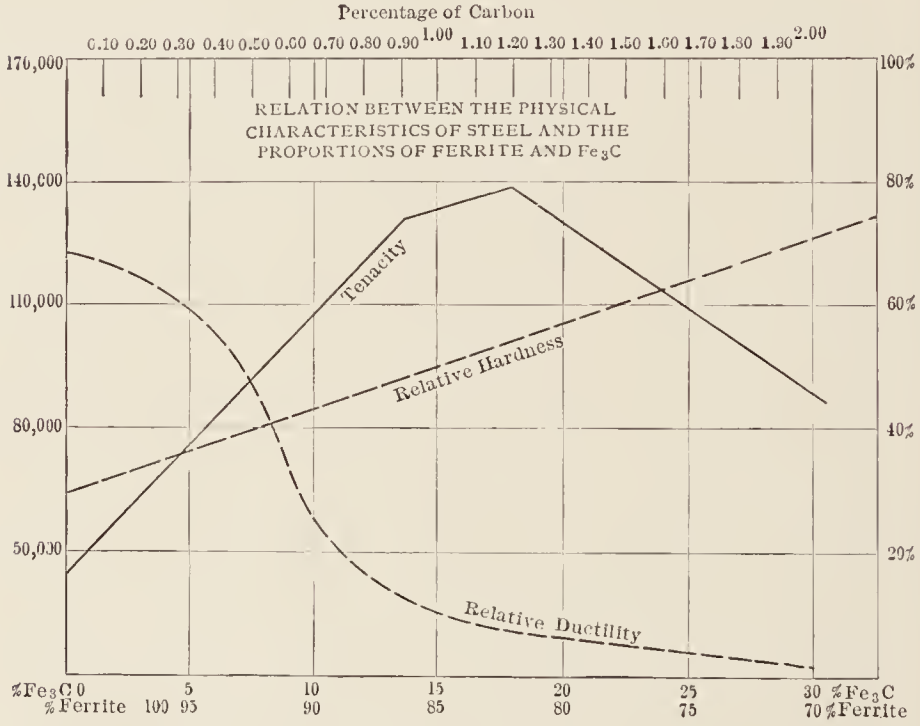


FIG. 267.—From Howe, "Iron, Steel, and other Alloys."

carbon will increase the strength by 1000 lb. per square inch in the case of acid open-hearth steel, and by 770 lb. per square inch in the case of basic open-hearth steel. Because the color method of determining the amount of carbon does not show all the carbon present, the figures given above must be replaced by 1140 lb. and 820 lb. for each 0.01 per cent. of carbon, when the color test is used. We have no data to determine the strengthening effect of carbon in Bessemer and crucible steel, but it is probable that a little lower value than that given for basic open-hearth steel would be used for Bessemer, and a little higher

[1] Page 391 of No. 2.

value than that given for acid open-hearth steel would be used for crucible steel.

Silicon.—The effect of silicon on strength is probably very small in the case of rolled steel. In the case of castings, however, an important increase in tensile strength may be obtained by increasing the silicon to 0.3 or 0.4 per cent. This practice results in practically no decrease in ductility, but it is necessary to supply larger risers on account of the deep piping that will be produced. It is probable that the beneficial effect of silicon in this case is due very largely to its producing soundness.

Sulphur.—H. H. Campbell says that the effect of sulphur on the strength of acid and basic open-hearth steel is very small. It is probable, however, that this statement is only true when the sulphur is in the form of manganese sulphide, because the effect of iron sulphide would be to lower the strength and the ductility of the material. The worst effect of sulphur is undoubtedly its production of "red-shortness" and the liability to cause checking during rolling, or, in the case of a casting, during cooling.

Phosphorus.—Campbell states that each 0.01 per cent. of phosphorus increases the strength of the steel by 1000 lb. per square inch. It should be observed, however, that this increase of strength is measured by the resistance of the material to stresses slowly applied and that it ceases with 0.12 per cent. phosphorus and is reversed. In the case of vibratory stresses and sudden shocks, phosphorus is probably the most harmful of the elements, so that it is undesirable to increase the strength of steel by means of this element. This is the more true because of the brittleness produced by phosphorus, for an increase of strength obtained through this medium is accompanied by a much greater decrease in ductility than when the same increase in strength is obtained through the medium of carbon.

Manganese.—The beneficial effect of manganese on tensile strength begins, according to the same authority, only when the manganese is above 0.3 or 0.4 per cent. With less manganese than this, in the case of open-hearth and Bessemer steels, the presence of some other condition, probably iron oxide, masks the effect of manganese. It will be remembered that when the manganese is low, open-hearth and Bessemer steels are harmfully charged with oxygen. Furthermore, the effect of manganese is dependent upon the amount of carbon present.

In acid open-hearth steel each 0.01 per cent. of manganese (beginning at 0.4 per cent.) increases the strength 80 lb. per square inch when the carbon is 0.1 per cent., but each increase of 0.01 per cent. of carbon increases the strengthening effect of manganese by 8 lb. So that, for example, if we have an acid open-hearth steel containing 0.4 per cent. of carbon, then each 0.01 per cent. of manganese will increase the strength by 320 lb. per square inch. In the case of basic steel each 0.01 per cent. of manganese (beginning at 0.3 per cent.) increases the strength 130 lb. per square inch when the carbon is 0.1 per cent., and so on to 250 lb. per square inch when the carbon is 0.4 per cent., for each additional 0.01 per cent. of carbon increases the strengthening effect of manganese on basic steel by 4 lb. (See Table XXVI.)

Formulæ.—Campbell gives the following formulæ for the strength of acid and basic open-hearth steels:

For acid steel: $40{,}000+1000C+1000P+xMn+R=$ ultimate strength.
For basic steel: $41{,}500+770C+1000P+yMn+R=$ ultimate strength.

In these formulæ, $C=0.01$ per cent. carbon (determined by combustion), $P=0.01$ per cent. phosphorus, $Mn=0.01$ per cent. manganese, and $R=$ a variable, depending upon the heat treatment which the steel has received. For X and Y see Table XXVI.

TABLE XXVI.—EFFECT OF EACH 0.01 PER CENT. MANGANESE ON OPEN-HEARTH STEEL

Percentage of Carbon	On Acid Steel X	On Basic Steel Y
	Lb. per sq. in.	Lb. per sq. in.
0.05	.....	110[2]
0.10	80[1]	130
0.15	120	150
0.20	160	170
0.25	200	190
0.30	240	210
0.35	280	230
0.40	320	250
0.45	360	.....
0.50	400	.....
0.55	440	.....
0.60	480	.....

[1] Begininng only with 0.4 per cent. of manganese.
[2] Beginning only with 0.3 per cent. of manganese.

Copper.—Copper, up to at least 1 per. cent., does not appear to have any important effect upon the strength or ductility of low- and medium-carbon steels, but increases the brittleness of steel containing 1 per cent. carbon. When the sulphur is more than 0.05 per cent. copper appears to make the steel roll less easily and above 0.5 per cent. of copper appears to make high-carbon steel draw less easily into wire.

Arsenic.—Some steels contain arsenic, which does not appear to have any effect when it is below 0.17 per cent., but any larger quantity raises the tensile strength and decreases the ductility to a very important extent.

Oxide of Iron.—All Bessemer and open-hearth steels contain more or less oxide of iron, there probably being more in basic steel than in acid, and more in Bessemer steel than in basic open-hearth steel. It is probable that this oxide of iron has not any very marked effect upon strength, as Campbell quotes some steels containing quantities larger than usual whose strength is good. No data are given as to the ductility, however, and it is probable that oxide of iron has a deleterious effect upon this quality.

Hardness and Brittleness of Steel

As a general thing the hardness and brittleness of steel increase together. The chief commercial application of this property is in such articles as railroad rails and car-wheels, bevel- and spur-gears, axles and bearings, the wearing parts of crushing machinery, etc.[1] To produce hardness in these materials carbon is the chief agent used, because it gives the maximum hardness with the least brittleness. It is for this reason that railroad rails are now made up to 0.7 per cent. carbon, and although this material is somewhat brittle and breakages occasionally occur, the high carbon is demanded in order that the head of the rail may be durable. Phosphorus increases both the hardness and the brittleness, especially under shock. Manganese likewise increases hardness, and especially the kind of hardness which makes it more difficult and more expensive to machine the metal. With more than about 1 per cent. of manganese the steel becomes somewhat brittle. When the content rises above 2 per cent. the steel is so brittle as to be practically worthless. In this connec-

[1] I purposely omit here the consideration of such hardness as that produced in springs, cutting tools, etc., by heating the steel to a bright-red heat and plunging into water, as this will be discussed in Chapter XIV.

tion a curious phenomenon is observed, in that a still further increase in manganese produces a reversal of its influence, and when we have more than 7 per cent. the metal is not only extremely hard and practically impossible to machine commercially, but becomes, after heat treatment, very ductile and tough. This will be considered more fully in Chapter XV.

Silicon.—Silicon makes the steel slightly harder, but apparently without increasing its brittleness, unless we have more than 0.5 or 0.6 per cent.

Electric Conductivity of Steel

The purer the material and the nearer it is to ferrite, the better will be its electric conductivity; therefore only wrought iron, or the softest and purest forms of steel, are used generally for wire for electric conduits.[1] The case is somewhat complicated when we come to third rails for electric railroads, which have now become a very important industrial product, because so pure a material will be very soft and will rapidly wear away under the abrasion of the contact-shoes. To increase the hardness of these rails with the least decrease in electric conductivity, it is best to avoid nickel and manganese, which decrease electric conductivity in greater proportion than the other elements, and to obtain the hardness as much as possible from phosphorus, and not from carbon, because phosphorus will give the greatest amount of hardness with the least decrease in the purity of the iron. As high phosphorus steels are difficult to roll, however, the section of the rail chosen should be as free as possible from sharp corners and thin flanges, in order that the tearing action in rolling may be as slight as possible.

Magnetic Properties of Steel

Alpha ferrite is the chief magnetic constituent of iron and steel, and therefore the greater the amount of this constituent present, the greater will be the magnetic force and magnetic permeability and the less its magnetic hysteresis. On this account the cores of electromagnets, the armatures of dynamos, etc., are commonly made of Swedish wrought iron, which is the purest commercial form of iron made.[2]

[1] Omitting, of course, the use of copper.

[2] A silicon alloy of iron with a double-heat treatment discovered by R. A. Hadfield, and having a very high magnetic force and permeability, will be discussed under the head of "Alloy Steels."

Ferrite has no permanent magnetism, but immediately loses its magnetic force when it is out of contact with a magnet, or, in the case of cores of electric magnets, when the electric current is cut off. Permanent magnets are therefore made of a high-carbon steel (1 per cent.), whose strength and permanency are increased if about 5 per cent. of tungsten is present. This steel is heated above the critical temperature and hardened in water, after which it is magnetized by causing an electric current to flow around it for a short time. Steel so treated will retain the magnetic force for many years. Osmond has explained the permanent magnetism of steel in the following very ingenious manner: Each molecule of alpha ferrite is believed to have a north and a south magnetic

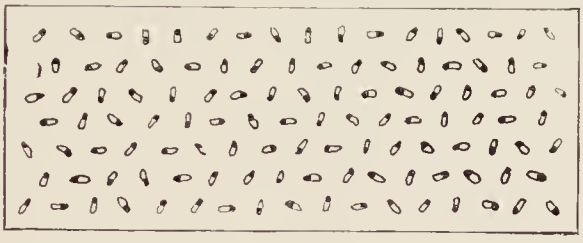


FIG. 268.

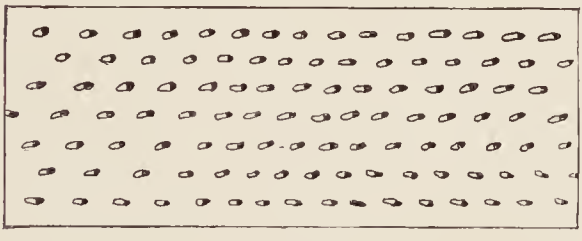


FIG. 269.

pole, which, in the ordinary unmagnetized condition of the iron, will be oriented in many different directions, as shown in Fig. 268. When this piece of iron in placed in the magnetic field, however, the molecules arrange themselves in accordance with the lines of magnetic force, with their north poles all in one direction and their south poles all in the opposite direction, thus making the whole piece of iron a magnet. As soon as the magnetic force is removed, however, the molecules all return to their original orientation, and the whole piece of iron loses its magnetism. We have already learned that it is only the alpha molecules which have north and south magnetic poles, and if the steel consists entirely of beta or gamma molecules, it is not capable of becom-

ing magnetic. According to Osmond's theory, when steel is cooled rapidly from above the critical temperature, the shortness of the time taken in reaching the atmospheric temperature is such that only a part of the molecules are able to change to the alpha allotropic form, and the remainder are retained in the gamma form. This retention is assisted by the 1 per cent. of carbon present, which acts as a brake to make the change slower. When, now, this hardened steel is subjected to the magnetic force, the alpha molecules orient themselves with their north poles all in one direction; but when the magnetic force is removed there is a certain number of gamma molecules present to interfere with the free movement of the alpha molecules and prevent them from returning to the original unoriented position. This explanation implies that the magnetic force is sufficient to overcome the resistance of the gamma molecules and force the alpha molecules into a magnetic position, but that the force of the alpha molecules tending to return to their original position is not so great.

The welding of steel and the effect of different elements upon it will be discussed in Chapter XIV.

XII

THE CONSTITUTION OF CAST IRON

Practically all the cast iron which is not purified is used for making iron castings, so that a study of the constitution of cast iron resolves itself into a study of iron castings. The difference between cast iron and steel is that the former contains less iron and more impurities, especially carbon, silicon, phosphorus, and occasionally sulphur and manganese. The advantages of cast iron, and the reason it is used as much as it is, are its fluidity, lesser amount of shrinkage when cooling from the molten state, relative freedom from checking in cooling, and the ease with which very different properties are conferred upon it at will. Its disadvantages are its weakness and lack of ductility and malleability. The last-named deficiency renders it practically impossible to put any work upon cast iron; hence it can never be wrought to shape and must always be used in the form of castings. Its most important advantages are probably its ready fusibility, which makes it so easy to melt and cast, and its cheapness.

Graphite.—All of the characteristic qualities of cast iron are due to the presence of the large amount of impurities in it. These impurities are the same in kind as the impurities in steel, and differ only in amount, with the single exception of graphite. This constituent is almost never found in steel, or is found in a very small number of cases, those cases being confined to the high-carbon steels, the amount of which is very small in comparison. In cast iron, however, graphite is the largest and one of the most important constituents. It occurs in thin flakes, in sizes varying from microscopic proportions to an eighth of a square inch in area,[1] disseminated through the body of the metal and forming an intimate mechanical mixture, a magnified section of which is shown in Fig. 279. Each flake of graphite is composed of smaller flakes, built up somewhat like the sheets of mica with which all are familiar, but with very little adhesion

[1] In rare and unusual cases the flakes of graphite may be as much as an inch and a half to two square inches in area, but practically never so large in the commercial cast irons.

between the small component flakes, so that the sheet of graphite may be split apart with very little force. Graphite is very light in weight, having a specific gravity of only about 2.25 as compared with a specific gravity of 7.86 for pure iron; consequently although the percentage of graphite by weight is only 4 per cent. or less of the iron, its percentage by volume may be, in normal cases, as much as 14 per cent. This may readily be seen by noting the amount of space occupied by the graphite flakes in Fig. 279.

Combined Carbon.—We have already discussed the solidification and slow cooling of cast iron, and it will be remembered that all the carbon which does not precipitate as graphite forms first as austenite, which later decomposes into ferrite and cementite. In short, all the carbon in slowly-cooled cast iron will ultimately be found partly in the form of graphite and partly in the form of cementite. The carbon of cementite in cast iron commonly goes under the name of "combined carbon," but it must be remembered that cementite is the constituent which gives the observed effects. Unless the cooling is very slow, some carbon will be in the austenitic or dissolved form.

White Cast Iron.—In slowly-cooled white cast iron the carbon, amounting often to 3 or 4 per cent., will all be in the form of cementite, which will therefore form 45 to 60 per cent. of the material; consequently white cast iron will possess largely the properties of cementite. It is very hard and brittle, being machined only with the greatest difficulty and with special kinds of cutting tools, and resisting wear by abrasion very effectively. It is so brittle as to be readily broken by the blows of a hammer, and is weak because of the presence of very large plates of cementite, which adhere but slightly to one another. Consequently white cast iron has few uses and is employed usually only as a hard surface on the outside of gray-iron castings.

Gray Cast Iron.—Gray cast iron may have about the same total amount of impurities present as white cast iron, the only difference then being that the carbon is partly or wholly precipitated as graphite. The gray color of a freshly broken fracture, from which this material receives its name, is due altogether to the graphite present, for this constituent is so weak that the iron breaks chiefly through its crystals, which are rent asunder, leaving one part sticking to each side of the fracture. The weakness of gray cast iron as compared with steel is thus

readily understood, since there is but a small proportion of metallic surface to be broken and the graphite splits so easily. An interesting experiment is to take a freshly broken surface of gray pig iron and brush one-half of it for some time with a stiff brush. In this way the adhering crystals of graphite are partially removed and we get a surface which is almost as white as the fracture of white cast iron. This shows clearly that the gray color is due altogether to the graphite and that the metallic part is as silvery white as iron itself. The prevalence of the gray color also shows how completely fracture takes place through the graphite crystals.

Gray cast-iron castings are by far the more important, and the study of their constitution is the chief object of this chapter. These castings usually contain 2 per cent. or more of graphite and less than 1 1/2 per cent. of combined carbon. It will be observed that this limit of combined carbon is also the range found in steel. Furthermore, it will be observed that the graphite is not a chemical component of the metallic body, but is mechanically mingled with it. In this sense, therefore, we may consider gray cast iron as a very impure steel,[1] mechanically mixed with graphite, and upon this reasoning the study of its constitution becomes much simpler,[2] as we may study first the properties of the metallic part, and next that of the graphite, and so be able to foretell to some extent the properties of the mixture. Indeed, the properties of the metallic part are already understood pretty well from our knowledge of the constitution of steel, and there is no new constituent or new condition except the larger amounts of silicon and phosphorus, which are of minor importance, because their effect is collectively far less than the weakening and embrittling effect of the graphite. Even though we had a very pure metallic constituent, the strength and ductility of this portion would not be sufficient to prevent the mass as a whole breaking at a small load and without exhibiting any practical ductility, because of the weakening effect of the crystals of graphite. In other words, it is the carbon which is the great factor in determin-

[1] The silicon in gray cast iron is usually between 0.75 per cent. and 3 per cent., or, let us say, ten times that in steel, while the phosphorus is usually from 0.5 to 1.5 per cent., or, again, about ten or more times that in steel. The sulphur varies greatly, but is not infrequently as high as 0.15 to 0.2 per cent. Manganese is an exception and is usually no higher in cast-iron castings than in steel.

[2] This theory of the constitution, which meets with very favorable acceptance in many quarters, was independently evolved by J. E. Johnson, (*American Machinist*, 1900), and H. M. Howe (*Trans. A. I. M. E.*, 1901, vol. xxxi, pp. 318–339).

ing the properties of cast iron, for this may be either all graphitic, or all combined, or part in both conditions.

Total Carbon.—By running the blast furnace very hot, we may extend the saturation point of the iron for carbon and thus get a slightly higher total carbon. This is not a very potent influence, however, for we seldom have total carbon more than 4.5 per cent., or less than 3.25 per cent. This control, such as it is, may be exercised either during the manufacture of the pig iron or during the remelting in the cupola, because in the latter furnace the liquid iron is in contact with coke and will absorb carbon up to its saturation point at the existing temperature.

Rate of Cooling.—A far more potent effect on the properties of the metal is the transfer of carbon from the graphitic into the combined form, or vice versa, by rapid or by slow cooling from the molten condition. It will be remembered that the carbon is always dissolved in the iron when the mass is in a molten condition, that is, when it is above the lines AB and BC in Fig. 253. As we cool from the molten state, graphite precipitates, but this cooling must be very slow indeed for this normal chemical change to take place completely. If, therefore, we cool with great rapidity, as, for example, by pouring the iron into a metallic mold which "chills" it, or by some other form of artificial rapid cooling, we may prevent the precipitation of graphite, by denying the time necessary for the chemical reaction, and obtain a metal in which all the carbon is in the combined form,[1] i.e., white cast iron. It is also evident that, by a rate of cooling intermediate between this rapid rate and the slow rate which permits the precipitation of the normal amount of graphite, we may obtain an intermediate amount of carbon in the graphitic form. Rapid cooling is a very important means of "chilling" the surfaces of gray-iron castings, whereby we may have a relatively soft gray iron in the interior of each article and a hard surface. For example, chilled-iron rolls are made in this way (see page 187), and also American railroad car wheels[2] which are cast against an iron chill (see page 336), giving nearly an inch depth of white iron around the tread and flange where the metal

[1] The term combined here is used to include chemical combination or solution.

[2] In other important railroad countries it is more usual to have the car wheels made of steel, as it is believed that the iron wheels are not sufficiently strong and ductile. The manufacture of pressed-steel car wheels is increasing in America; nevertheless, the chilled cast-iron wheels seem to give very good service.

is to suffer abrasion in grinding over the rails, while the web and bore will be of gray cast iron, because cooled more slowly in the sand part of the mold, and thus will be less brittle, and better able to withstand the shocks of service and may be machined easily.

The Effect of Carbon on Cast Iron

The nature and constitution of gray cast iron is far more difficult to understand than that of steel, and even greater is the difficulty of predicting the effect of any change in composition or in constituents. The chief reason for this complexity is that a change in any one of the constituents of gray cast iron is liable to effect changes in several others as well. The simplest example of this is in the case of the carbon; we have total carbon, graphite, and combined carbon, and if we change any one of these three, we must change either one or both of the other two, and it makes a great deal of difference which. Indeed, we almost never change the amount of graphite without making the reverse change in the amount of combined carbon, and vice versa. Thus a very loose system of speaking of these matters has come into vogue among foundrymen. For instance, it is very common to hear a foundryman say: "In order to soften your iron, increase the graphite"; but what he really means is: "In order to soften your iron, decrease the combined carbon." He knows that the one change usually follows from the other, and he speaks of it in this way, regardless of the fact that graphite can be increased (i.e., by increasing the total carbon and leaving the combined carbon the same or a little higher), and yet the iron will not be made any softer, but may even be harder.

Graphite and Shrinkage.—The most important effect of graphite on cast iron, aside from causing weakness, is in decreasing the shrinkage. The reason for this will be understood when we consider what happens when cast iron solidifies. It will be remembered that when the eutectic forms, the cast iron breaks up into alternate plates of graphite and austenite. This separation of graphite from solution is the birth of a new constituent, and this constituent occupies space, so that there is an expansion of the mass as a whole in proportion to the amount of graphite that separates. If, therefore, we pour liquid cast iron into a mold, which is, of course, entirely filled at the moment when the iron begins to solidify, the first action that takes place after the

beginning of solidification is an expansion, due to the separation of graphite. The expansion continues for several moments until the chemical precipitation is completed, after which the metal begins to contract, as all metals do in cooling from a high temperature; but the preliminary expansion has been so great that the ultimate shrinkage may be only about one-half what it otherwise

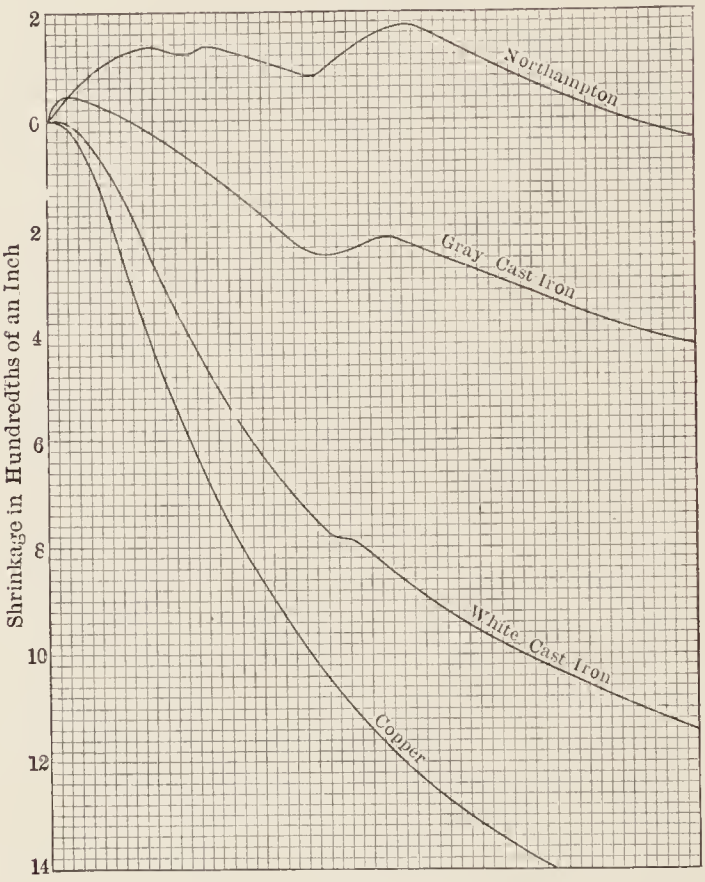


FIG. 275.—SHRINKAGE CURVES.

would have been. We can thus control this shrinkage by controlling the amount of the expansion, through varying the graphite. This point will be more readily understood by referring to Fig. 275, which is taken from an article by Prof. Thomas Turner of England.[1]

Explanation of Fig. 275.—The point *O* marks the position occupied by the end of the bars at the moment of solidification. It will be seen that in the case of copper the metal contracts con-

[1] *Journal of the Iron and Steel Institute*, No. 1, 1906, page 57.

tinuously from this point, as shown by the continuous drop of the curve. In the case of white cast iron, the metal contracts continuously until we reach a certain point (which is at a temperature of about 665° C.), when a momentary arrest of the shrinkage takes place, after which the metal again contracts. This arrest is common to all cast iron and steel and marks the decomposition of austenite at the point *S*, Fig. 252, page 295. Now, see what a difference there is in the case of gray cast iron, which does not shrink immediately after freezing, but expands very appreciably, as shown by the rise in the curve. This expansion is due to the graphite that is being expelled from the metal and occupies space between the particles of iron.

Again, in the case of the Northampton iron, which is high in both graphite and phosphorus, the expansion is very long-continued, and the metal cools to almost a black heat before the bar has shrunk again to the size it had when first cast. This expansion is again due to the separation of carbon, and is assisted apparently by the phosphorus keeping the iron in a semifluid condition for a long time and thus allowing the graphite more easily to separate and make place for itself. Here, too, we have an explanation why phosphoriferous irons fill every crevice of the molds so perfectly. Being in a pasty condition for some time, and continually expanding, the semifluid metal is forced into the tiniest crevices of the molds, filling all the corners with astonishing sharpness.

It is evident that any increase in graphite, whether caused by an increase in total carbon or by a decrease in combined carbon, will produce less shrinkage. The extent of this may be judged by noting that gray cast iron expands so much in solidifying that no contraction cavity or pipe is formed, such as occurs in the case of steel. If the iron is only slightly gray, or if it is a very large section of metal, then a slight spongy place may be formed in the center, which is the nearest approach to a shrinkage cavity that is normally found in most iron castings.

Graphite and Porosity.—It is also evident that an increase in graphite, whether produced by an increase in total carbon or by a decrease in combined carbon, will increase the porosity of the casting, which is often disadvantageous, as in the case of hydraulic cylinders or other receptacles for holding liquids under pressure. The separation of much graphite usually is accompanied by large-sized graphite crystals, and therefore the crystals

of the mass, as revealed by the fracture, appear large and the grain is said to be "open."

Graphite and Workability.—When we come to consider the effect of graphite upon the softness or workability of the cast iron, it is evident that we must consider it in relation to other things; for if we increase the graphite by increasing the total carbon, then we increase the workability of the metal only in so far as the graphite acts as a lubricant for the tool that is doing the cutting. Evidently the tool will have no difficulty in cutting through the soft flakes of graphite; the chief resistance to it will be given by the metallic part of the mixture. Though the lubricating effect of the graphite undoubtedly helps the tool, its presence evidently cannot increase the actual softness of the metallic body with which it is mixed. But, on the other hand, if we increase the graphite by decreasing the combined carbon, then we have not only increased the amount of lubricant, but we have, in addition, increased the softness of the metallic part of the mixture by reducing the proportion of cementite in it.

Graphite and Strength.—Everything else being equal, it is evident that the more graphite we have in cast iron, the weaker it will be, for we have already shown that gray cast iron breaks by the ready splitting apart of the flakes of graphite. Thus, if we make no change in the combined carbon, but increase the total carbon of our castings, and consequently the graphite, we should expect a corresponding decrease in strength, and this is in fact found to occur. When, however, we increase the graphite and at the same time decrease the combined carbon, we may or may not get an increase in strength, this depending altogether on how much combined carbon there was before and after the change. For example, if we had 3 per cent. of combined carbon and 1 per cent. of graphite in a casting, that casting would be weak because of too high combined carbon. To decrease this and increase the graphite would have a beneficial effect on strength. On the other hand, if we had 1 per cent. of combined carbon and 3 per cent. of graphite, to decrease the combined carbon and increase the graphite would have a detrimental effect on strength. We must therefore consider the question of strength from a much larger viewpoint than by considering any one constituent alone.

Combined Carbon and Shrinkage.—Combined carbon has very little effect on the shrinkage of cast iron except in so far as it

changes the graphite. That is to say, if by increasing the combined carbon we decrease the graphite, we will get an increase in shrinkage, and vice versa.

The Effect of Silicon, Sulphur, Phosphorus, and Manganese on Pig Iron

The constitution of cast iron is, furthermore, very complicated because of the double influence of silicon, sulphur, phosphorus, and manganese. Each of these elements has a direct influence upon the properties of the material, which is in general similar to its influence upon steel. For example, silicon produces freedom from oxides and blow-holes and makes the iron more fluid; manganese counteracts the effect of sulphur and increases the difficulty of machining the material; sulphur makes the metal very tender at a red heat, and therefore liable to checking if put under strain during this period. For example, if a casting in shrinking tends to crush the sand, this strain will be more liable to break it in case the sulphur is high. Sulphur also makes solidification take place more rapidly, and causes blow-holes and dirty iron. Phosphorus makes the metal very fluid and reduces its melting-point. It also makes it more brittle under shock, especially when cold, and produces a fusible eutectic, a photomicrograph of which is shown in Fig. 266. Phosphorus and sulphur increase the tendency to segregate.

Furthermore, the various compounds of the impurities with iron and with each other, which we find in steel, are also found in cast iron. Indeed, some of them are far more important in the latter than in the former, because the amount of the impurities is greater. This is especially true of manganese sulphide and iron sulphide, for the sulphur in cast iron is often large in amount, while the manganese is often intentionally small on account of the difficulty which this element produces in the machining of the casting. Therefore we are even more liable to find iron sulphide in cast iron than in steel.

But the direct effect of these impurities is usually far less important than their indirect effect, namely, their influence upon the carbon. After all, it is the carbon which is the chief factor in controlling the most important properties of the cast iron, and we may vary this either by increasing or decreasing the total amount, or else leaving the total amount the same, by increasing the graphite and decreasing the combined carbon, or vice versa.

It is the ease with which we may vary the amount or the condition of the carbon, and therefore the properties of the iron, that is one of the most important advantages of the material. But, strangely enough, although it is easy to keep this control, it can never be accomplished in a direct way. It will be remembered (see pages 29 to 32), that the blast-furnace manager can vary the amount of silicon and sulphur in his pig iron at will; that he has only a small control over the manganese and practically none over the phosphorus or carbon, but that the metal always saturates itself with this latter element; and it has also been seen (see page 318) that the limit of this saturation is small.

Silicon.—By means of his control over the silicon and sulphur, the metallurgist exercises indirectly his most important control over the condition of the carbon; for silicon acts as a precipitant of carbon, driving it out of combination and into the graphitic form, so that with about 3 per cent. of silicon, slow cooling and very low sulphur and manganese, we may obtain a cast iron in which almost none of the carbon is in the form of cementite. That is to say, the presence of this amount of silicon acts so strongly that it may partially prevent the formation of austenite during solidification, and also cause graphite to precipitate instead of cementite at 690° C. (1275° F.) when the eutectoid decomposes (point *S*, Fig. 252, page 295), so that it decomposes into ferrite and graphite instead of ferrite and cementite. The maximum precipitation of graphite seems to occur with about 2.5 to 3.5 per cent. of silicon. With each increase of silicon up to that point (the amount of sulphur, the rate of cooling, and other influential conditions remaining the same), we get an increase in the amount of graphite precipitation, but when the amount of silicon exceeds about 3 per cent. it seems to reverse its effect, and each addition of silicon thereafter causes an increase in the proportion, not of graphite, but of combined carbon. At this point large amounts of various iron silicides (Fe_2Si, Fe_2Si_2, etc.), make their appearance. Then the color of a freshly broken fracture begins to be bright like a mirror, in contradistinction to the white color of ordinary white cast iron, which has more nearly the appearance of frosted silver.

Sulphur.—The influence of sulphur upon the formation of graphite is almost the exact opposite of the influence of silicon. That is to say, each increase in the amount of sulphur present increases the amount of combined carbon in the iron. It is

usually considered that each 0.01 per cent. of sulphur will neutralize fifteen times as much silicon (i.e., 0.15 per cent.) in its effect upon the condition of the carbon in the iron. It is also very important to note that when the sulphur is in the form of MnS, it is not so potent in increasing the combined carbon as when it is in the form of FeS. An interesting example of this is shown in the analysis of the two railroad car wheels given below:

	Fe	Total Carbon	Si	Mn	P	S	Graphite	C.C.
Good wheel.	94.79	3.84	0.69	0.13	0.43	0.12	3.30	0.54
Poor wheel..	95.00	3.52	0.65	0.12	0.52	0.19	2.35	1.17

Good wheel required 150 blows of 25-lb. sledge to break it. Poor wheel required 8 blows of 25-lb. sledge to break it.

It will be observed that the poor wheel has more than twice as much combined carbon as the good wheel, although the sulphur in the poor wheel is only about 50 per cent. more than the sulphur in the good wheel, the other impurities being nearly the same. When we come to figure out the amount of MnS and FeS in the two wheels, we find, however, the explanation of the large amount of combined carbon in the poor wheel. We also have an explanation of the poor quality of this wheel in the increased amount of FeS present.

Constituent	Good wheel per cent.	Bad wheel per cent.
MnS	0.206	0.195
FeS	0.121	0.315
FeSi	2.045	1.923
Fe_3P	2.755	3.335
Pearlite	67.610	84.492
Ferrite	23.963	0.000
Cementite	0.000	7.390
Graphite	3.300	2.350
Totals	100.000	100.000

Manganese.—Manganese increases the total carbon in pig iron. Manganese also increases the proportion of the carbon that is in the combined form, but its influence in this respect is far less than that of the sulphur; moreover, the statement requires the following qualification: as much manganese as is combined with sulphur in the form of MnS does not increase the proportion of carbon in the combined form. Indeed, it has really the reverse effect, because it takes the sulphur out of the form of FeS, in which it is most powerful in increasing the combined carbon. In this sense, therefore, the manganese actually decreases the amount of combined carbon.

The excess manganese over that necessary to form MnS (that is, the manganese in the form of $[FeMn]_3C$) increases the proportion of carbon in the combined form, and also increases the amount of total carbon even more potently than does the manganese, which is in the form of MnS. We therefore have a strange contradiction, in that when the manganese is high an increase in sulphur will, by decreasing the amount of $(FeMn)_3C$, actually decrease the tendency of manganese to raise the total carbon as well as the combined carbon. To sum up, manganese and sulphur both tend to increase the total carbon and the combined carbon, and yet they neutralize each other in this respect.

Phosphorus.—The effect of phosphorus upon the carbon is somewhat self-contradictory; from a chemical standpoint it tends to increase the proportion of combined carbon, and this is especially true when the silicon is low and the phosphorus high (say above 1.25 per cent.). But phosphorus also has the effect of lengthening the period of solidification. That is to say, it makes the iron pass through a somewhat mushy stage of solidification, and this mushy stage lasts for several minutes. This lengthening of the solidification period gives a longer time in which graphite can precipitate. Therefore, when the silicon is relatively high (at least over 1 per cent.), and there is consequently a strong tendency for graphite to precipitate during solidification, this precipitation is actually aided by the phosphorus, and the graphite occurs not only more abundantly, but in larger-sized flakes. When, however, the amount of phosphorus is very large, its chemical effect is great enough to retain the carbon in the combined form, in spite of the long period of solidification. We may sum this up by saying that if the chemical conditions are such that graphite is bound to precipitate, then the physical effect of

the phosphorus makes this precipitation the more easy; but if there is enough phosphorus present to produce a strong chemical effect of its own, or if the other chemical influence is not very powerful (i.e., if the silicon is low), then phosphorus tends to keep the carbon in the combined form.

The Properties of Cast Iron

Let us now consider the properties of cast iron, and summarize under the head of each the influence of the various elements and conditions upon them.

Shrinkage.—The shrinkage of cast iron is of more importance than might at first appear, because the greater it is the greater will be the strains set up in the cooling of the casting, and consequently the liability to check; also, the greater will be the allowance necessary in order that the casting may be true to the size called for by the drawings. Graphite is the most important impurity in this connection, because of the expansion which its separation causes. This separation should take place at the moment of solidification, but is usually not complete then, and therefore the precipitation continues during the fall of the temperature to several degrees below the freezing-point. Furthermore, when the silicon is high, graphite instead of cementite separates at the lower critical point (i.e., the line PSK in Fig. 253, page 296). As silicon and the rate of cooling are the chief influences which control the separation of graphite, they become the governing factors in the shrinkage of the iron. Indeed, when sulphur is practically normal and no other unusual conditions prevail, there is such a close relation between the size of the castings[1] and the percentage of silicon on the one hand, and the amount of shrinkage on the other hand, that any one of the three may be calculated when the other two are known.

Sulphur is important in this connection, and its effect is contrary to that of silicon, because of its tendency to retain the carbon in the combined form. Manganese and phosphorus each has a less important influence. Manganese, by increasing the total carbon, tends to increase graphite and therefore decrease shrinkage. So far as it neutralizes sulphur, moreover, its effect is in the same direction. Phosphorus decreases shrinkage, both because it contributes to the fluidity of the metal and therefore

[1] Which is the chief influential feature in the rate of cooling.

gives a better opportunity for carbon to separate, and also because of the expansion caused when the phosphorus eutectic separates from solution. A hotter casting temperature of the iron has the effect of increasing combined carbon.

TABLE XXVII.—RELATION OF SHRINKAGE TO SIZE AND PERCENTAGE OF SILICON

Per. cent. of silicon	½ in. square	1 in. square	2 in. × 1 in.	2 in. square	3 in. square	4 in. square	Perpedicular readings show decrease due to increase in silicon.
1.00	.183	.158	.146	.130	.113	.102	
1.50	.171	.145	.133	.117	.098	.087	Horizontal readings show decrease of shrinkage due to size.
2.00	.159	.133	.121	.104	.085	.074	
2.50	.147	.121	.108	.092	.073	.060	
3.00	.135	.108	.095	.077	.059	.045	
3.50	.123	.095	.082	.065	.046	.032	

A table showing the relation between the size of the casting, the amount of silicon, and the shrinkage, is given above and is taken from No. 93. Slight changes must be made in this table by each foundry for the conditions of sulphur, phosphorus, temperature, etc., obtaining there; but those given herewith will be found sufficiently accurate for all ordinary purposes where conditions are anywhere near normal.

Shrinkage Tests.—At many foundries it is the custom to make a shrinkage test of the iron from each cupola at least once a day. The simplest way of making these tests is to pour into a mold 12 in. long, with a sectional area approximately proportionate to the size of the castings made, some of the iron from about the middle of the cupola run. The casting must be poured flat, and the difference between 12 in. and the length of the cold bar is the shrinkage of the metal. This method is somewhat crude and, although it gives valuable results, has been greatly improved by W. J. Keep[1] and Prof. T. Turner,[2] who have devised simple and inexpensive pieces of apparatus whereby the iron, after it begins its solidification, draws a curve showing first the expansion and later the contraction. It is by means of Professor Turner's apparatus that the curves shown in Fig. 275, page 320, were made.

[1] See Chapter XX of No. 93.
[2] Reference on page 320.

With very little care these curves can be obtained to show with sufficient accuracy for all ordinary purposes the percentage of graphite and also (other conditions being normal, or nearly so), the percentages of silicon and combined carbon, and the strength, hardness, and porosity. Indeed the curves are more useful than many single tests, because they show at a glance the net effect of several varying conditions.

Density.—The maximum density of gray cast iron occurs with about 1 per cent. of silicon. With less than that, the iron is liable to contain spongy spots, due to high shrinkage on account of low graphite. With more silicon the separation of graphite decreases density. Above 2 per cent. of silicon, the grain of the iron becomes so open as to be actually porous and the density falls off by 12 per cent.

TABLE OF DENSITES.

	Specific gravity	Weight per cubic foot
Pure iron	7.86	490
White cast iron	7.60	474
Mottled cast iron	7.35	458
Light gray cast iron	7.20	450
Dark gray cast iron	6.80	425
Sample of gray cast iron when cold	7.17	448
Same, when liquid	6.65	416

To make a close-grained iron for hydraulic work the sulphur should be from 0.03 to 0.055 per cent. If more than this, the iron is liable to be dirty, to contain spongy spots on account of low graphite, to be difficult to machine on account of high combined carbon, and to be weak, because high sulphur, aside from its effect on carbon, reduces the strength. Especially, if the phosphorus is high must the sulphur be kept down to these limits, or the iron will be hard, brittle, and weak.

There should be from 0.4 to 0.6 per cent. of manganese. We do not want more manganese than this, or the casting will be difficult to machine. We do not want less than I have indicated, because manganese assists in counteracting the bad effects of sulphur and phosphorus.

Phosphorus has a double-acting influence on the porosity of cast iron: (1) It increases the size of the crystals, decreases shrinkage and causes a large expansion after solidification, as explained in connection with Fig. 275; but (2) it fills all the crevices between the crystals and in the interior of the iron, which, by decreasing the porosity, counteracts its first influence. When the phosphorus is high, the phosphorous and iron form a eutectic, which remains fluid for a long time and fills the tiniest crevices in the interior of the metal. For this reason iron for hydraulic work may run up to 0.7 per cent. phosphorus, but above that the iron is liable to be weak and "cold-short," especially under impact. In fact, where very strong iron is desired, the phosphorus should be kept down to 0.4 per cent. at least.

With the various amounts of impurities mentioned above the combined carbon will be in the neighborhood of 1 per cent. and the graphite about 2.5 per cent., the exact amounts depending upon the thickness of the castings and the rate at which they are cooled. If we desire to keep the combined carbon the same and reduce the graphite it will be necessary to reduce the total carbon. This can be accomplished by mixing in steel scrap and melting fast in the cupola, or by melting in an air-furnace instead of a cupola. This reduction in graphite results in a closing of the grain of the steel, with consequent increase in strength and density.

Segregation.—A common cause of porosity in castings is segregation, or the collection together of impurities in spots. This segregation is the greater the greater the amounts of phosphorus, sulphur, manganese, and silicon. Phosphorus increases the segregation by making a fluid eutectic, which does not solidify until after the remainder of the casting, but then runs into that part of the metal having the loosest texture. This part is usually in the middle of the larger sections of the casting, and when the silicon is high and there are shrinkage spots the segregation will be excessive in the neighborhood of these spots. Manganese and sulphur are also liable to collect in the same way and place. These localities, where the segregation is high, and which are known, when very bad, as "hot spots," are sometimes porous or surrounded by porous parts of the casting. They are sometimes so extremely hard that no tool will cut them. One way of getting rid of them is to use very large risers, or headers, which solidify last and serve as feeders for the remainder of the

metal. Under these circumstances the segregation occurs in the riser, and is thus temporarily removed. This method is not advisable as a regular practice, however, because these risers ultimately find their way back into the cupola as scrap and result in increasing the impurities in a subsequent set of castings.

Headers themselves increase the density of iron castings by feeding the metal and so preventing the porous spots, and also by keeping the metal under a pressure during solidification. This latter is especially serviceable when the phosphorus is high, which tends to make the metal expand during solidification, as I have shown.

Checking.—The time when a casting usually checks is when it is just above the black heat, when the metal is in a weak and tender condition and, as shown by Fig. 275, page 320, is under strain because it is contracting upon the sand. Sulphur greatly increases weakness at this temperature, because both sulphide of manganese and sulphide of iron are now in a pasty condition, and therefore offer very little resistance to breaking. The sulphide of iron is much worse, however, because this is spread out in thin plates or membranes which offer much more extended planes of weakness than the sulphide of manganese, which is in small spots or bubbles, resembling blow-holes in its effect. Phosphorus, by decreasing shrinkage, decreases the liability of checking, but phosphorus has another influence, shown in the production of large-sized crystals, and in this respect it increases the liability of the metal to check.

Manganese, by decreasing the size of crystals, tends to counteract partially the effect of the phosphorus. The size of crystals can also be decreased to some extent by chilling the weak points and feeding them well under a head of metal. Feeding all localities liable to check has the double advantage of lessening shrinkage and segregation, both of which increases the liability to checking.

Softness, Workability, and Strength.—It is the combined carbon which is the great hardener of cast iron, the other elements producing hardness chiefly in proportion as they produce combined carbon, except manganese, which not only produces combined carbon, but also produces a compound having the formula $(FeMn)_3C$, which is very hard and difficult to machine.

Silicon, by decreasing combined carbon, decreases hardness. When we get above 3 per cent. silicon, however, there begin to form new compounds with silicon which make the iron hard. Furthermore, silicon above 3 per cent. increases combined carbon, instead of decreasing it.

The maximum softness of cast iron is obtained with about 2.5 to 3 per cent. of silicon, the sulphur being not above 0.1 per cent. and the manganese not above 0.4 per cent. In large or slowly cooled castings the silicon should be near the lower limit, and in small or rapidly cooled castings near the upper limit, in order that the combined carbon may be down below 0.15 per cent. and the graphite more than 3 per cent. Such a cast iron would correspond to a soft steel, mechanically mixed with crystals of graphite. This soft steel would machine with great ease, and the graphite would act as a lubricant for the cutting tool. The mixture will have a transverse strength of about 2000 to 2200 lb., will be low in density and open in grain. To increase the strength without increasing the hardness, the best way is to cut the sulphur and phosphorus down to a low point, if possible, because sulphur, and next to it phosphorus, are the impurities which weaken iron most (aside from their influence on carbon). Another way is to decrease the total carbon, and hence the graphite, because graphite crystals, especially if large, are great weakeners of cast iron.

The strength of steel is more than double the strength of cast iron, the difference being due to almost altogether to the graphite in cast iron, because silicon in itself (aside from its influence on the carbon) is a strengthener of both iron and steel up to at least 4 per cent.

To a slight extent the total carbon may be reduced by melting steel scrap with the iron, or by decreasing the amount of manganese, provided that the manganese left be always at least twice the sulphur, otherwise the iron will be weak and brittle.

The strength of cast iron may be increased by increasing the combined carbon, but this is done at the expense of softness and workability. Cast iron containing from 1.5 to 2 per cent. of silicon (depending upon the size of the castings and rate of cooling), 0.9 per cent. of combined carbon, 0.5 per cent. of manganese and not more than 0.08 per cent. of sulphur and 0.3 per cent. of phosphorus, will work without difficulty in the

machine shop and have a tensile strength of over 28,000 lb. per square inch. In many cases foundries are unwilling to go to the expense of such a low sulphur and phosphorus. In this case the strength must be obtained by raising the manganese, which is not advisable, as it decreases the softness more than any other element, causes dull iron and high total carbon.

An important point in connection with the strength of cast iron is the size of the crystals of graphite—the smaller these crystals are the greater the strength, because the smaller are the planes of easy rupture. A notable example of this is malleable cast iron, which may have a tensile strength of 45,000 lb. per square inch, even when the percentage of graphitic or temper carbon is as high as 3 per cent. The very small size of the flakes of the temper carbon does not reduce the strength as much as the same amount of the larger graphite crystals.

It is believed by many that smaller graphite crystals are obtained by mixing different brands of iron in the cupola, even though the analysis of the mixture may be the same. This, however, is denied by others, and no reliable data exist upon which we can base a definite statement. It is also believed by many that when the silicon is added to the cast iron immediately before pouring into the molds, the crystals of graphite are smaller than those formed when high-silicon irons are melted in the cupola. The practice of adding a small amount of ferrosilicon to the ladle of cast iron after it is received from the cupola is thus said to be doubly advantageous, because the silicon does not have to go through the cupola, where it suffers some oxidation, and it produces the desired softness by precipitating the graphite, but in a form which does not decrease strength so much.

To obtain high transverse strength, the silicon should be about 0.2 per cent. lower and the combined carbon about 0.2 per cent. higher than the figures given for tensile strength. Otherwise the effects are very similar.

Some estimates of the strength and workability of cast iron are given in the following table,[1] and in No. 94:

Chills.—In the making of cast-iron rolls, railroad car wheels, anvils, etc., at least one surface of the casting is desired to have great hardness, to resist wear, and to be backed by metal which shall be stronger and not so brittle. This is accomplished by

[1] Abstracted from page 197 of No 120.

TABLE OF CAST-IRON STRENGTH AND WORKABILITY

	Silicon per cent.	Sulphur per cent.	Phosphorus per cent.	Manganese per cent.	Tensile strength lb.	Transverse strength lb.
Soft iron for pulleys, small castings, good tooling	2.20 to 2.80	Not over 0.085	Not over 0.70	0.30 to 0.70	28,000	2200
Medium iron for engine cylinders, gears, etc.	1.40 to 2.00	Not over 0.085	Not over 0.70	0.30 to 0.70	30,000	2500
Hard-iron cylinders for ammonia, air-compressors, etc.	1.20 to[1] 1.60 1.60 to[2] 1.90	Not over 0.095	0.70 to 0.40	Not over 0.60	25,000	2800

chilling the surface which it is desired to harden, and so producing white cast iron to varying depths, reglated at the will of the foundrymen. The making of this kind of casting is one of the most difficult problems of cast-iron metallurgy. The metal must be very close to the given composition, and the temperature of the mold, of the chill, and of the metal when cast must be regulated with care. Therefore, air-furnaces[3] are often employed for melting in this class of work, or else uniform conditions of cupola melting are maintained with great care, and very little, if any, scrap which must necessarily be of somewhat uncertain analysis is used, except the return scrap from the foundry itself, that is, defective castings, sprues, gates, shot-iron spillings, etc., and also scrap castings of like nature, such as worn-out car wheels and broken rolls. The most important factors in regulating the depth of the chill are the silicon and the sulphur, and in the following table is given the depth of clear chill from the surface for several different percentages of silicon and sulphur. The figures here given must only be taken as approximations, as they will vary to an important extent with different conditions in each foundry; but, starting with this as a

[1] If annealed. [2] If cooled fast. [3] See page 343.

FIG. 276.—WHITE PIG IRON.
0.75 per cent. Si. 0.120 per cent. S. 50 diameters. Unetched.

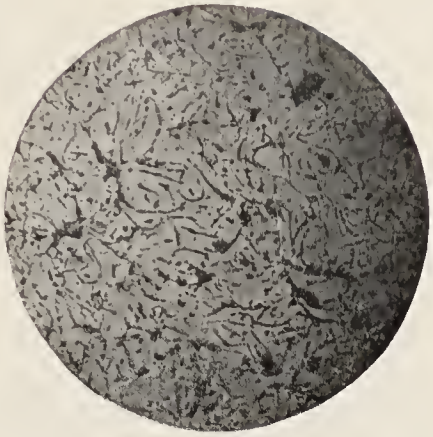


FIG. 277.—GRAY PIG IRON.
0.75 per cent. Si. 0.012 per cent. S. 50 diameters. Unetched.

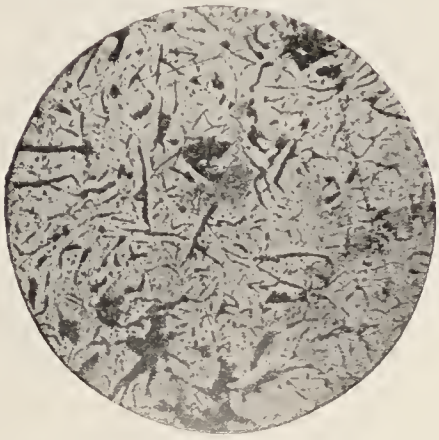


FIG. 278.—GRAY PIG IRON.
1.75 per cent. Si. 0.025 per cent. S. 50 diameters. Unetched.

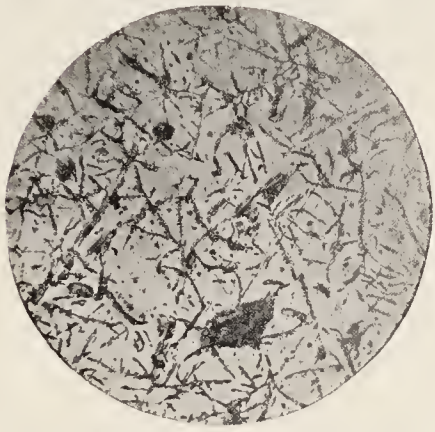


FIG. 279.—GRAY PIG IRON.
2.5 per cent. Si. 0.012 per cent. S. 50 diameters. Unetched.

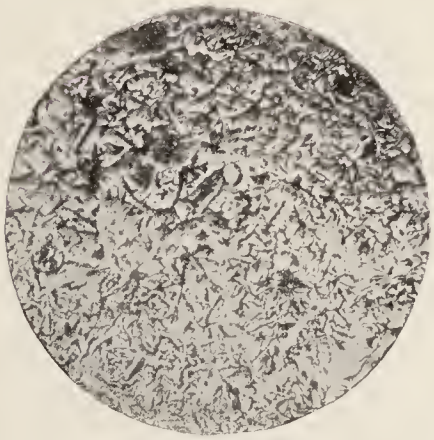


FIG. 280.—GRAY PIG IRON.
3.5 per cent. Si. 0.025 per cent. S. 50 diameters. Unetched.

FIG. 281.—NO. 2 CHARCOAL PIG IRON VERY SLOWLY COOLED.
50 diameters. HNO_3.

basis, one can quickly prepare a table for himself to suit the practice in his foundry. Phosphorus has very little effect on the depth of chill, and manganese is also relatively less effective,

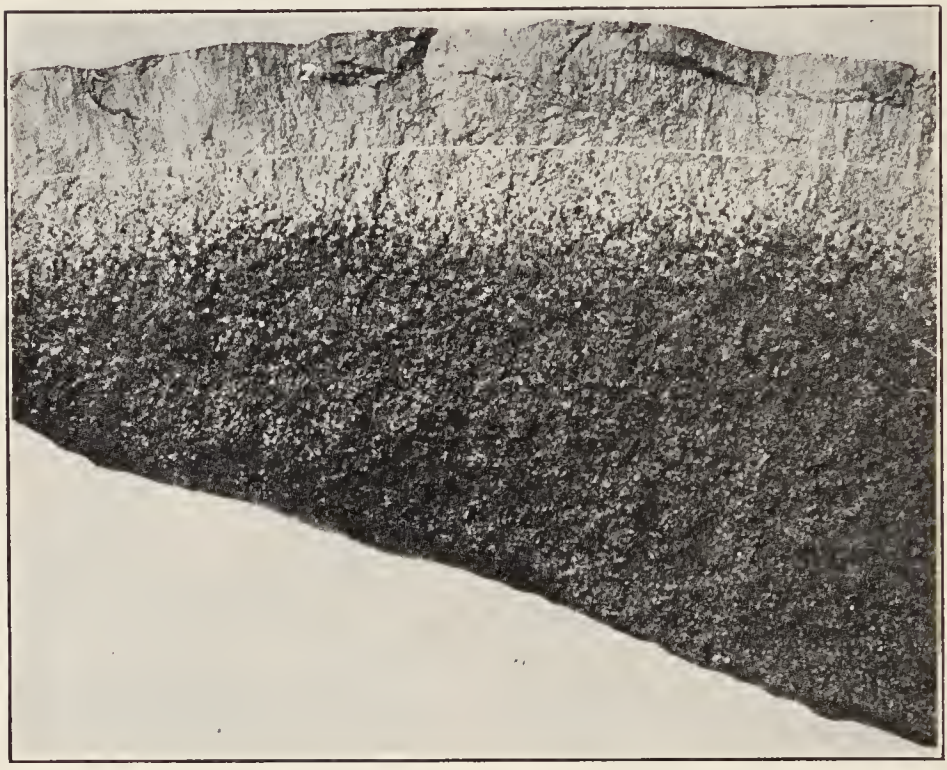


FIG. 282.—METHOD OF MEASURING THE DEPTH OF CLEAR CHILL IN A CAST-IRON ROLL.

although it increases the hardness of the chilled portion. The hotter the iron when cast the deeper the chill.

DEPTH OF CLEAR CHILL FROM SURFACE IN INCHES

Silicon per cent.	Sulphur 0.2 per cent.	Sulphur 0.15 per cent.	Sulphur 0.1 per cent.	Sulphur 0.075 per cent.	Sulphur 0.05 per cent.
1.25	0.625	0.250	0.125	0.000	0.000
1.00	1.000	0.625	0.250	0.125	0.000
0.75	1.500	1.000	0.625	0.250	0.125
0.50		1.500	1.000	0.625	0.250
0.40			1.250	1.000	0.625
0.30				1.500	1.000

Casting Temperature of Iron.—The strength of cast iron is materially effected by the temperature at which it is cast. Longmuir (Reference No. 123) found that the tensile strength of iron, when cast too hot, was 33 per cent. less, and when cast too cold was 26 per cent. less than the same metal cast at the correct temperature. For the cast iron with which he experimented, the correct temperature of casting seemed to be in the neighborhood of 1230° C. (2246° F.).

XIII

MALLEABLE CAST IRON

Malleable cast iron has physical properties between gray iron and steel castings. Its tensile strength will vary between 40,000 and 60,000 lb. per sq. in. with an elongation of 2 1/2 to 5 1/2 per cent. in 2 in. and a reduction of area of 2 1/2 to 8 per cent.[1] In a transverse test, a 1-in. square bar on supports 12 in. apart, should bear a load as the center of at least 3000 lb. with a maximum deflection of 1/2 in.; the maximum load may go as high as 5000 lb. and the deflection up to 2 in. or more. In respect to its resistance to repeated stresses and to blows which flatten the face of the material without extending their influence very deep, malleable cast iron is especially valuable. It also has great resiliency and (when very thin) is capable of being flattened out or bent double without cracking. A good test for malleable cast iron is the so-called test lug shown in Fig. 285. These are bent over in the form of a curled-up shaving by light blows of a hammer, beginning at the knife edge. The distance along the test wedge that the piece will bend before it begins to break, and especially the maximum angle produced, will give a good idea of the softness of the material.

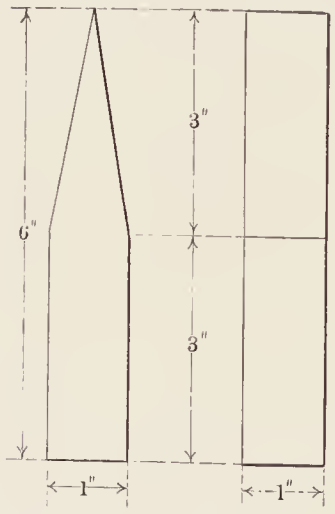


FIG. 285.—TEST LUG FOR MALLEABLE CAST IRON.

Malleable iron castings are used very largely for railroad work. They have long been used for couplers, but are now being replaced to some extent by steel castings for this purpose. On the other hand, malleable cast iron is replacing gray cast iron for other parts, such as journal boxes. Malleable cast iron is also used very largely for parts of argicultural machinery, for

[1] In the case of iron very carefully melted and anncaled in iron oxide, the elongation may go as high as 10 per cent., and the reduction of area as high as 12 per cent. in rare cases.

pipe fittings—i.e., elbows, unions, valves, etc.—for household and harness hardware and a great variety of work where many castings are to be made of the same pattern, especially castings of small size. Even hammers, hatchets, skates, wood chisels, etc., are often made of "black heart" malleable cast iron.

Process of Manufacture.—The process, which was invented by Réaumur in 1722, but has only been in practical use about 100 years, and of importance less than 50, is still followed out in substantially its original form in England and Europe to make what is known as "white heart" malleable castings. In America this process has been modified to make the so-called "black heart" castings, as follows: The metal is melted and cast into molds of the desired shape and size, and after cooling its fracture will be entirely white, or else white with a small area of mottled iron in the center of pieces 1 in. thick or heavier. In short the composition of the metal is such that it is just on the line between the precipitation of graphite and its retention in the form of cementite and dissolved carbon. In all cases the majority of the carbon must be dissolved or combined. After carefully cleaning, the castings are reheated to a temperature of 625° to 875° C. (1250° to 1600° F.), which is roughly 450° C. below their melting-point. They are kept at this temperature for some 60 hours and under these conditions occurs the precipitation of graphite, which normally should have occurred during the first cooling. In the majority of cases almost all the combined carbon throughout the body of the casting is changed to graphite. But the graphite does not here form in flakes, as in ordinary gray cast iron, but in a finely comminuted condition, like a powder, to which the name of "temper carbon" or "temper graphite" is given (see Fig. 286). In this form it is not nearly so weakening or embrittling to the casting as flakes of graphite would be.[1]

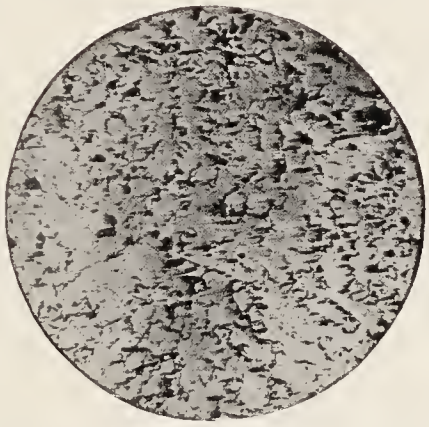


FIG. 286.—ANNEALED MALLEABLE CAST IRON.
Magnified 50 diameters. Unetched.

A broken fracture of such an annealed casting will have a

[1] We may liken this to two samples of putty, in one of which had been embedded a large number of plates of mica, and in the other the same amount of mica ground to powder.

black center with a rim of white, 1/64 to 1/16 of an inch thick around the outside. The dark center owes its appearance to the precipitated temper carbon, and the white outer rim consists of iron from which the carbon has not been only precipitated, but actually removed.[1] That is, the metal of this outer rim corresponds to a soft steel impregnated with a great number of tiny cavities formerly occupied by carbon and which act as a cushion to shocks and battering blows of service. This outer rim is the portion of the casting in which the metallic crystals have formed perpendicularly to the cooling surface as explained on page 248. The crystalline form in this location favors the reaction for the mechanical removal of carbon which will be explained later.

The Manufacture of Réaumur, or White Heart Malleable.—In the original, and present European, process of making malleable castings, they are made very thin; they are then annealed at the higher temperatures given above and for a period nearly twice as long, with the result that the conditions described above as prevailing in the outer rim, extend here throughout the entire casting. In short, the carbon is mechanically removed, even from the center portion. White heart castings are not as strong as black heart and rarely, if ever, are above 1/2 in. in thickness.

Manufacture of All-black Castings.—In America pipe fittings and other castings not requiring much strength are sometimes annealed in lime, fireclay, or some other substance which does not decarburize even the skin of the metal. This results in the carbon being deposited as temper carbon, but not being removed. The castings are several thousand pounds per square inch lower in tensile strength, and have substantially no white rim.

Pig Iron Used.—The analysis of the "hard castings," that is, the white castings before the annealing process, should run as follows:

	If melted in cupola	If melted in air furnace or open hearth
Silicon, per cent	0.75 to 1.25	0.45 to 1.00
Manganese, per cent	0.30	0.30
Phosphorus, per cent[2]	under 0.225	under 0.225
Sulphur, per cent[2]	0.04 to 0.32	0.04 to 0.07
Total carbon, per cent	above 2.75	above 2.75

[1] By the material in which they are packed according to the following reaction: $3C + Fe_2O_3 = 3CO + 2Fe$.

[2] In European practice the phosphorus and sulphur are often much higher than this.

This analysis is obtained by mixing pig iron with varying amounts of cast iron and steel scrap.

Not more than about 20 per cent. of bought scrap is used on the average in American practice, and a good deal of this is steel, on account of the desirability of lower total carbon, and because iron scrap is too impure, too variable, and too uncertain in sampling and chemical analysis for castings requiring strength, such as those for railroads and machinery. There is, however, always a large amount of "return scrap" from the foundry, consisting of defective castings, sprues, gates, etc., which, in the case of small castings, may be greater in weight than the castings themselves. This return scrap is low in total carbon and silicon as a result of having already suffered the melting changes. Steel scrap is, of course, a prime factor in reducing the total carbon. The return scrap should all be cleaned from adhering sand to avoid difficulty in melting. The pig iron bought for malleable iron work is known in the trade under the name of "coke malleable."

Silicon.—The proportion of silicon will depend upon the size of the casting and the amount of total carbon, because the greater each of these is the less will be the amount of silicon that will cause a precipitation. Furthermore, cupola metal requires more silicon by about 0.25 per cent. than air furnace metal because of the difficulty with which it yields to the annealing operation. It might at first appear that the less silicon the better; but this is not altogether so, because temper carbon will not come out during annealing unless a certain amount of silicon is present; and the more there is the more quickly, easily, and completely will the precipitation occur. For air furnace castings one inch thick the silicon may be as low as 0.35 per cent.; but this is unusual, as three-quarters of an inch thickness is rarely exceeded. For half-inch castings the silicon will be about 0.60 per cent., and for very thin and light castings with low total carbon and high sulphur (say 0.2 to 0.3 per cent.), the silicon may be up to 1 per cent. To the percentage of silicon desired in the castings, we must add the amount which will be burned out in melting. In the cupola this will be about 0.2 to 0.25 per cent., and in the air-furnace from 0.15 to 0.5 per cent., depending on the length of time the metal is kept in the furnace after melting. The hotter we want the iron, the longer this time must be, and therefore the higher the silicon in the original mixture charged.

Sulphur.—Sulphur increases the tendency of castings to check, which is especially important in malleable work on account of the contraction of white iron being nearly double that of gray iron. Sulphur also reduces the strength and the ease of annealing. For this reason over 0.06 per cent. should not be permitted in castings requiring strength, but it actually runs up to 0.2 and 0.3 per cent. in inferior metal, both in America and England, and especially in small castings, which do not need strength so much, and which, having less length for contraction are not so liable to be checked by cooling strains.

Manganese.—Low manganese is preferred by many foundries, and one of the highest authorities in America places the limit at 0.8 per cent. It should be remembered, however, that the manganese should be at least twice the sulphur, and preferably three times, except when the sulphur is as high as 0.3 per cent. Manganese of 0.5 per cent. tends to decrease checking. It also protects silicon from oxidation, both during melting and annealing, and on this account hastens and makes more complete the precipitation of temper carbon. It also protects the iron itself from oxidation during annealing and thus prevents the formation of "scaled" castings. More than 0.6 per cent. manganese makes the iron hard and difficult to machine, which is disadvantageous, especially for pipe-fittings, which must be threaded with great economy in order to meet the trade competition. It also makes the castings difficult to anneal.

Phosphorus.—Phosphorus makes the metal fluid, which is especially desirable where total carbon and silicon are low, or where sulphur and manganese are high. On the other hand, it diminishes two of the most valuable properties of the material: its resiliency and resistance to shocks. It also makes the metal hard, difficult to machine, and liable to check, and amounts over 0.225 per cent. should never be permitted by engineers where the castings are subjected to strain.

Total Carbon.—Total carbon below 2.75 per cent. gives trouble in annealing and therefore makes the castings weak. It also makes the metal more sluggish. It is difficult to get as low as this in cupola melting, although mixing in large percentages of steel scrap and allowing the metal to run out of the cupola as fast as melted will reduce the proportion appreciably. In air-furnace practice the total carbon may be reduced as far as necessary. Annealing in iron oxides also removes carbon from the outer

layers and even to the very center of thin castings. The lower the total carbon in the annealed castings, the better.

Melting in the Air-furnace.—The commonest melting-furnace for malleable cast iron is the air-furnace. After the metal is melted it is retained in this furnace for 15 minutes to an hour longer, and test ingots are poured at intervals, from the fracture of which and the temperature of the iron we determine the correct moment for tapping. The fracture of the test plug should be a clear white throughout, except when the castings are to be of very light section, in which case the metal might be tapped when the test sample shows a few specks of graphite in the center. The practice of judging from test plugs is different

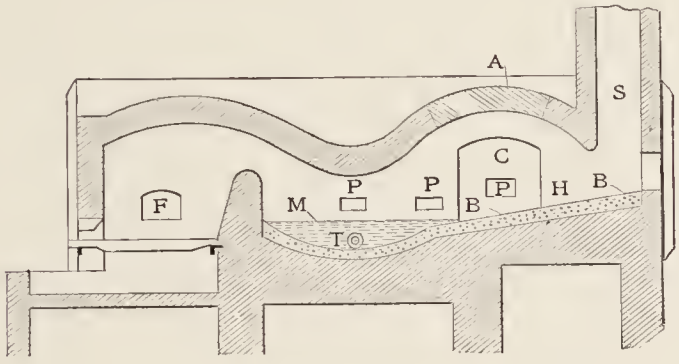


FIG. 287.

in each foundry, but there must be some system which insures that the metal shall be of such a composition when tapped that the castings will have not more than a trace of graphite if any at all (say, less than 0.15 per cent. in small castings and a little more in larger ones). If more than this the annealed castings will be very weak, almost "rotten."

The diameter of the test plug should be as large as any section of casting that is to be poured. The usual size is 1 1/2-inch diameter.

Air-furnace.—The air-furnace is a reverberatory furnace on the hearth of which pig iron in melted by radiation from the flame of a soft-coal fire, or, more rarely, from a gas flame. The furnace is charged by means of a large side door, or by removing the roof in sections bound together with iron, or by taking out the end; and in some cases, to effect an economy in labor, mechanical devices are employed for charging. Several designs of air-furnaces are shown in Figs. 287 to 290 inclusive.

Lining.—The lining of the bottom is made of silica sand of about the same composition as the acid open-hearth furnace, i.e., containing 95 per cent. or more of silica, with just enough

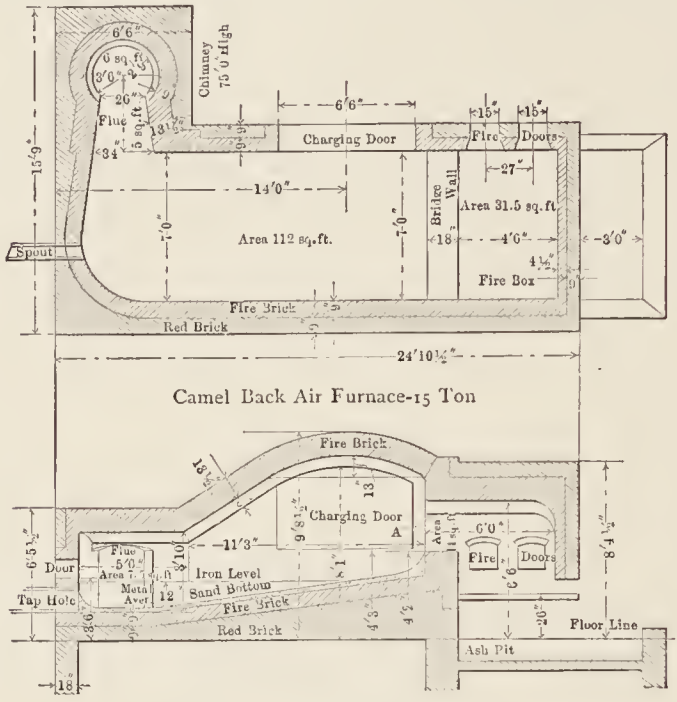


FIG. 288.—AIR-FURNACE.

lime to frit the mass together at the heat of the furnace. A layer about 1 to 2 in. thick is spread all over the hearth and then set on as described in the chapter dealing with the open-hearth

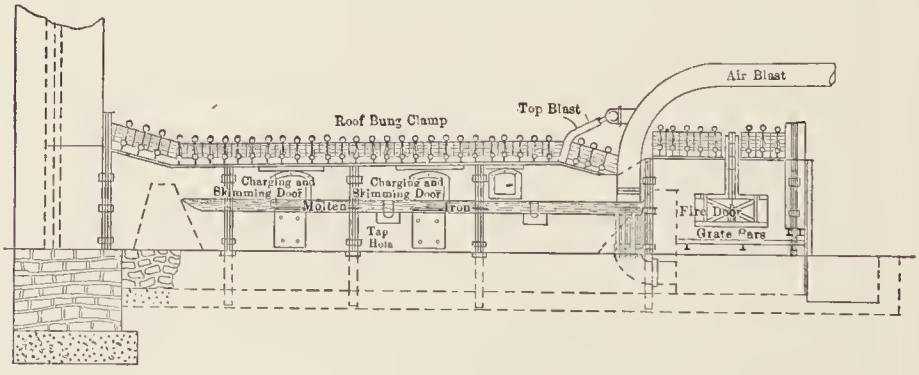


FIG. 289.

process. About five layers are put on in this way, and the bottom lasts on an average of 6 to 12 heats, although some foundries regularly make up a bottom after the third heat; and in other

cases the bottoms last as many as 30 heats. Longer life will be obtained if the material is charged carefully so as not to break the

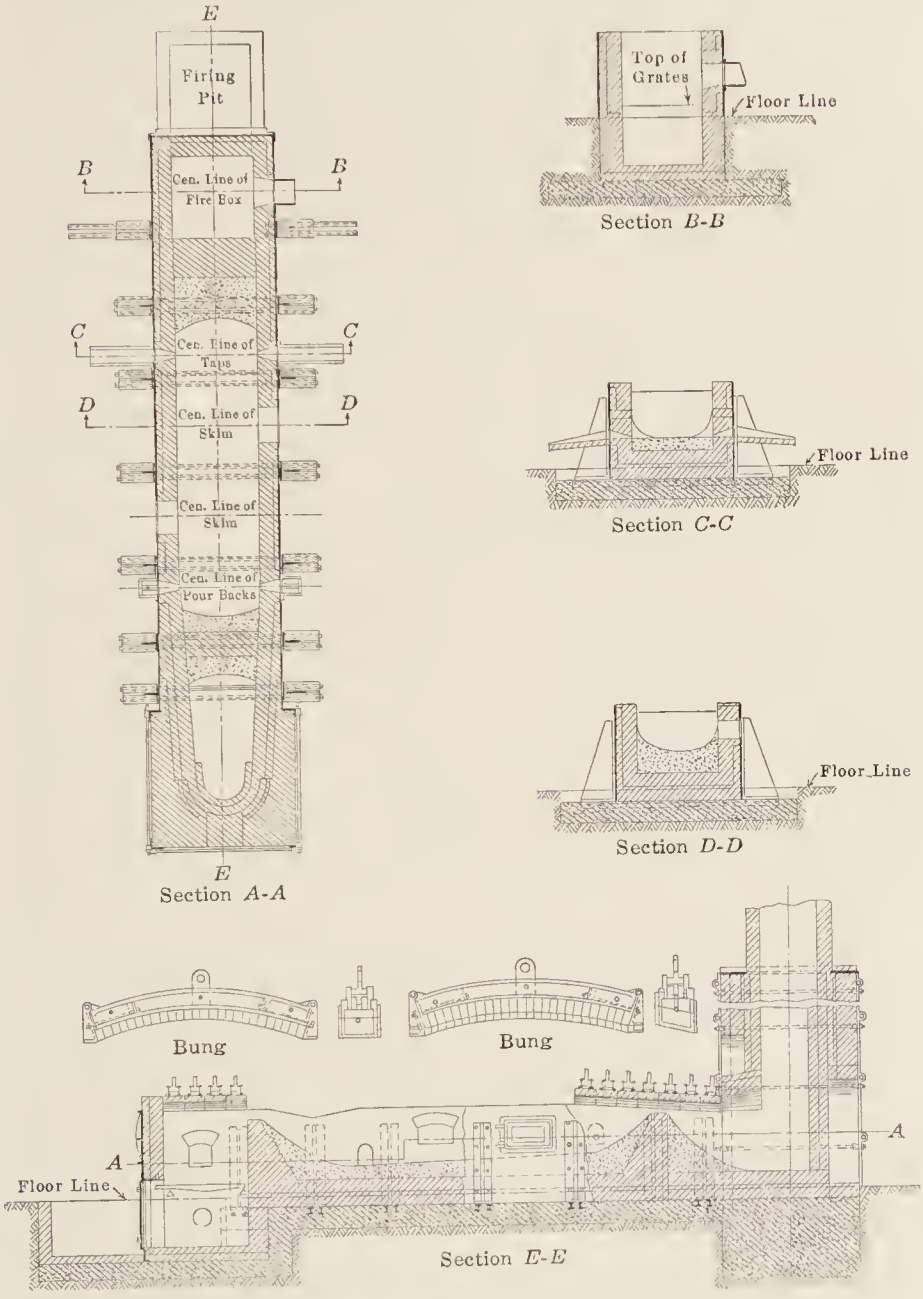


FIG. 290.

sand, and if a strongly reducing flame is maintained during the melting period, when there is not a bath of liquid iron to protect the bottom from the corrosive iron oxide. Mixing broken

fire-bricks of good quality and refractoriness with the sand seems to give more durable bottoms.

Charging.—The sprues and small scrap are first charged and spread evenly over the hearth and next the pig iron is piled in carefully. The roof of the furnace not being high, the pig iron must be stacked in order to get the necessary amount into the available space. Moreover, when the pig iron is stacked, individual pigs can be pushed down into the liquid bath from time to time so that it will not all melt together. Thus it can be handled more easily and the slag comes up better. The steel scrap is charged after the pig and scrap is melted and the slag has come up. This prevents the steel scrap from being oxidized.

Conduct of the Operation.—The purpose of the furnace is to melt the iron and bring it to the proper temperature for casting. Some refining by oxidation is unavoidable, but this is not an intentional feature and the object should be to get the desired analysis by mixing pig iron, scrap, and steel, and not by the oxidation of silicon and carbon. A long time in the furnace after melting is especially to be avoided, as the iron is liable to be oxidized and the silicon reduced below the desired point, making the iron high. After the slag is up it should be skimmed off, and this may be repeated once or twice. When the test plug shows large, clear, white crystals without any pin holes on the rim, and only a slight amount of mottling, the bath is ready to tap. If there are pin holes in the rim of the test plug it indicates that the metal has been "burned," as it is called. It will usually be dull and there may even be gas in the metal, in which case the iron should be poured into pigs and used over again in small amounts in subsequent heats. If the test plug is mottled, it shows either that the silicon is too high or that the temperature is not high enough, for it will be remembered that the colder the iron the more likely is graphite to separate and vice versa. If the iron is too high, on the other hand, some ferro-silicon should be added and rabbled into the bath. The smaller the castings, the more rapidly will they be chilled and therefore the more silicon should we have in the metal.

American furnaces usually vary in size from 10 to 45 tons capacity, but they are built as small as 3 tons. It takes from about three and one-half to nine hours to melt down a charge of from 5 to 35 tons respectively, and the waste of metal by

oxidation will be about 2 to 5 per cent. of the charge. The fuel used should be a good grade of bituminous coal, and the amount about one-fourth of the weight of the charge.

Tapping the Charge.—The more rapidly the metal can be gotten out of the furnace and poured, the more uniform will be its composition. Moreover, the metal at the top of the bath is hotter than that at the bottom. For this reason, in many furnaces, there are additional tap holes at a higher level, which are opened first, and also holes on both sides of the furnace which are used simultaneously.

Cupola Versus Air Furnace Melting.—Cupolas used for melting malleable cast iron are similar to those already described but the amount of fuel is larger than for most gray iron work on account of the higher melting-point of the iron and the very small size of castings into which it is usually poured. The fuel ratio will be about one of coke to four of iron.

The advantages of the cupola for malleable cast iron work are: (1) That we get metal having practically the same composition at all times of the heat except the slightly higher sulphur at the beginning and end; (2) the temperature is more uniform throughout the heat; (3) it is cheaper to install and operate and requires less skill for melting labor; (4) it can be started and stopped more readily; (5) we can get hotter iron without prolonging the heat with the resultant danger of burning which exists in the air furnace.

The advantages of the air furnace are: (1) That there is not so much sulphur absorbed; (2) with proper manipulation there is not so much liability for the metal to be burned except just at the thin edge of metal near the fire bridge; (3) the metal anneals more easily and is stronger; (4) it is also easier to get a lower total carbon by proper mixing since there is no contact between coke and iron, and therefore not so much opportunity for absorption of carbon; (5) we can work closer to a desired analysis in the air furnace than we can in the cupola.

This latter circumstance, as well as the lower sulphur, is the reason why air furnaces are so largely used also for melting what is known as chilled iron castings, such as rolls, etc. The analysis of this chilled iron must be so closely confined within limits that the outside may be white iron where it comes in contact with metallic chills and the interior consist of gray cast iron.

The explanation of the more difficult annealing experienced

with cupola metal over air furnace and open hearth metal has never been made entirely clear. In general, cupola metal is high in sulphur which opposes annealing, but it is believed that even when the metal is of the same analysis in sulphur it requires at least 150° F. higher temperature to anneal it. Another circumstance in cupola metal is that it is usually higher in total carbon. Consequently the carbon must be more strongly held in combination to prevent some of it precipitating as graphite in the hard castings. This condition may cause it to yield less completely to the annealing process.

Open-hearth Furnaces.—Open-hearth furnaces of small size, but in other respects like the open-hearth steel furnaces, are used for melting iron for malleable castings in a few important foundries in the United States. The great drawback of this furnace is that it must be operated continuously, day and night, which means more floor space on which to set molds ready for pouring, because molding cannot well be done during the night, as the artificial light casts shadows that make the work of finishing up molds more difficult and confusing.

The advantage of the regenerative open-hearth furnace over the air-furnace is better control of the operation, and especially of the temperature, shorter heats, and greater fuel economy. The average time of melting in the open-hearth furnace will be 2 1/2 hours for a 10-ton heat, and 4 hours for one of 20 tons. The amount of fuel is about 300 to 350 lb. per ton of iron, or twice as much if melting only on the day turn. The lining will certainly last much longer on account of the better control of the character of flame. Moreover, oil can be used for melting in a regenerative furnace, because it is introduced into a very hot atmosphere, which is not practicable in the air-furnace, since the fuel condenses in the cooler atmosphere of this furnace, especially when the furnace is cold or when there is a cold charge on the hearth. The disadvantages are high cost for installation, more skilled labor and more repairs. Open-hearth linings are best made of dolomite, which enables a basic slag to be produced in the furnace and a reduction in phosphorus and sulphur. Cheaper pig iron and iron scrap can then be used. This basic lining is not attacked by the iron oxide and slag produced in melting and will last for hundreds of heats if not allowed to cool off too frequently. Basic linings cannot be employed in air-furnaces because dolomite contracts and expands so much on

cooling and heating that the bottoms are soon cracked to pieces, for air-furnaces are not operated continuously.

Molding and Pouring.—Malleable iron castings are usually made in great quantities from the same pattern, so that this industry offers a special field for molding machines, match plates, etc. It is also a type of molding in which a great many cores are used and especially cores of small size, so that core-making machines are especially advantageous where applicable.

FIG. 291.—TUMBLING-BARREL.

The gates and sprues are usually large in size because the metal has a relatively high melting-point and is consequently more liable to chill. For the same reason the metal is poured into the mold as fast as possible and the great bulk of the work is done with hand-ladles holding 40 or 50 lb. apiece.

Annealing-boxes.—After the castings are cooled they are carefully cleaned from all adhering sand by tumbling them around in a tumbling-barrel (in which they are mixed with star-shaped pieces of metal something like children's jackstones), or by sand-blast, or by some other suitable method. They are then packed

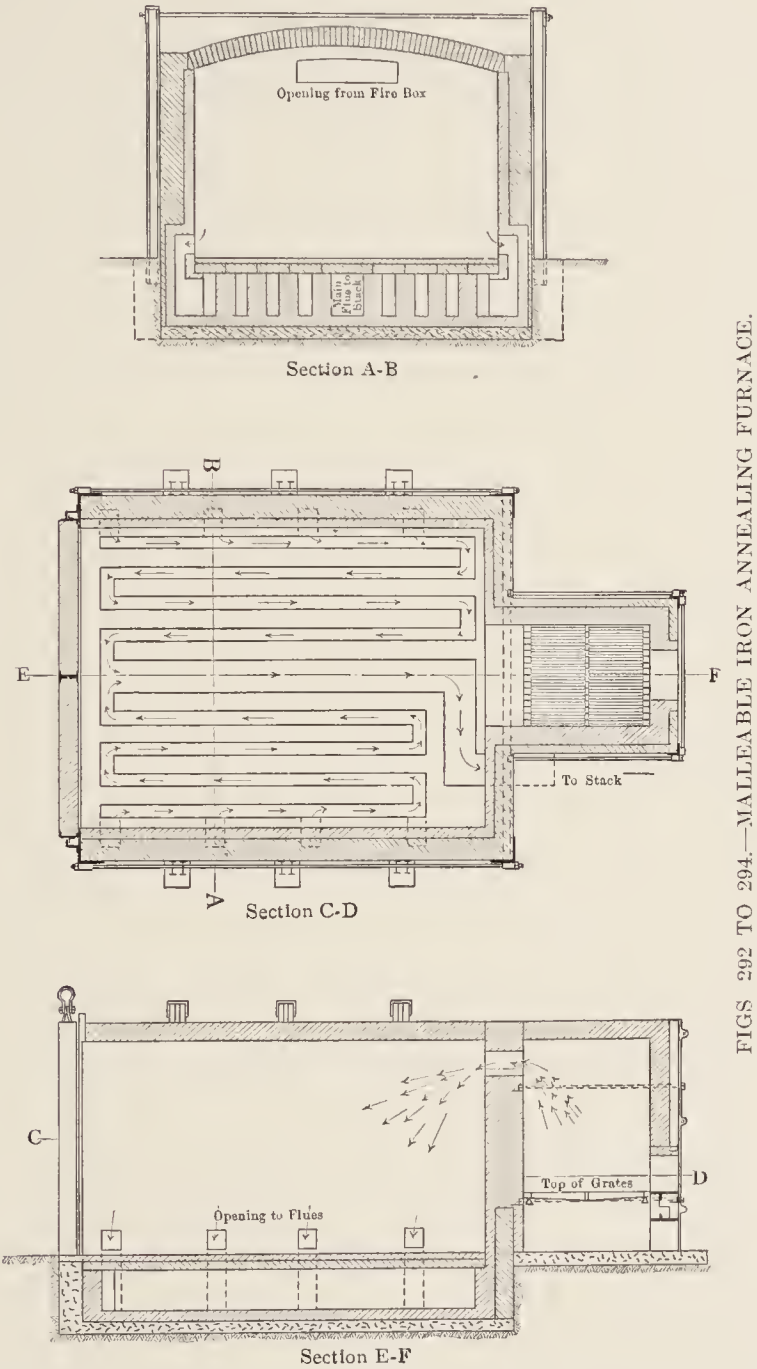
in the cast-iron or steel "saggers" or annealing pots, or boxes, together with the packing. Sometimes, though rarely, the tops of the saggers are closed by means of an iron cover, sometimes by a thick layer of the packing in the upper part, and sometimes by clay or wheel-swarf. These pots last only from 7 to 20 heats before they are largely oxidized away.

Annealing-ovens.—The boxes are then placed in the annealing-ovens in such a way that the flame may play around them as completely as possible. The general form of ovens is shown in Figs. 292 to 294. The flame usually comes in at the top and goes out at the bottom along the side, and thence through flues underneath the oven. The fuel used may be coke, coal, oil or gas, the latter being preferable on account of the better control of the temperature, which should be increased at a very gradual and uniform rate during the heating up, and kept as constant as possible during the annealing period.

Annealing Practice.—It takes about six days for the American annealing operation, including heating up and cooling down. Sometimes this can be shortened a little by decreasing the time at the full annealing heat, and by cooling rapidly or drawing the saggers out of the oven and dumping them while the contents are still at a dull-red heat. This practice is not conducive to a good quality of castings and should never be permitted in important cases. The time at the full heat should never be less than 60 hours, and preferably it should be more than that. If less, the temperature of annealing must be higher, and this decreases the strength and ductility of the castings. Annealing should not occupy too long a time, however, because the temper carbon tends to draw together to larger flakes; besides which the metal may become over annealed or else oxidized between the grains, i.e., "burnt." Air-furnace castings should be annealed at 675° to 760° C. (1250° to 1400° F.), and cupola metal at 825° to 875° C. (1500° to 1600° F.). The saggers are cooled as slowly as possible in the furnace; when they are at a black heat they are removed, cooled further and then dumped.

Packing.—As originally planned, the castings were annealed in a packing of iron oxide crushed to a size less than a quarter of an inch in diameter. The packing must surround the castings at every place, both inside and out, and no two castings must touch. Iron ore, mill scale, "bull-dog," and similar forms of iron oxide are used for this purpose.

Annealing in iron oxide produces a white skin where the casting has been deprived of its carbon, and a black interior, due to the



FIGS. 292 TO 294.—MALLEABLE IRON ANNEALING FURNACE.

temper carbon; whence the name of "black heart malleable" for this material. Tests have shown that the casting with this white

skin upon it is much stronger than a similar one which has not been decarborized on the surface, and therefore the packing in iron oxide is advantageous, even though not an essential feature of the operation. When the castings are packed in some non-oxidizing material, such as sand, clay or lime, they may receive as perfect an annealing, as far as the production of temper carbon is concerned, but will be without the white skin and of a lower strength.

Shrinkage.—Hard castings contract in solidifying much like steel, so that, wherever the metal is not "fed," it draws away leaving cracks or cavities. Therefore the castings may be considered as a continuous shell of metal on the outside with an interior full of cracks and planes of separation. In malleable cast iron work this is known as "shrinkage." It is a source of weakness in malleable castings, and is more effective in round than in square bars because the latter have a thicker solid skin on the corners which reduces the area of the cracked portion.

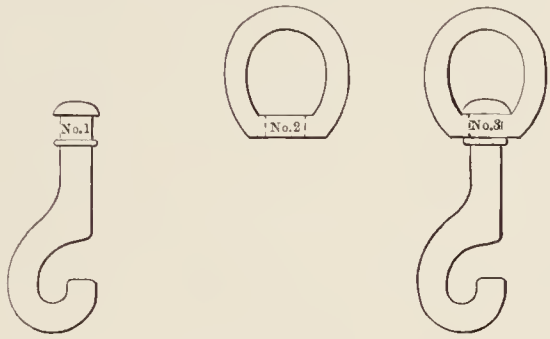
Contraction.—The contraction of the hard casting is almost as great as that of steel, because almost no graphite forms. The amount of silicon and the sectional area of the castings are still the determining factors in this connection. Indeed, by means of the measurement of the section and percentage of silicon we may estimate the contraction, or by means of the section and the contraction we may estimate the silicon very closely, other conditions and impurities being normal. The following table gives the necessary data for these estimations:

CONTRACTION IN INCHES PER FOOT OF LENGTH

Percentage of silicon	1/4 Inch square	1/2 Inch square	3/4 Inch square	1 Inch square
0.35	0.225	0.200	0.190	0.175
0.50	0.220	0.195	0.183	0.170
0.75	0.215	0.190	0.176	0.162
1.00	0.211	0.183	0.137	0.102

Expansion due to Temper Carbon.—It is a very interesting fact that when the malleable cast iron is annealed and the temper carbon precipitates, the casting expands to an amount approximately equal to that which would have occurred if the graphite

had separated during solidification and gray cast iron had been produced in the first instance. In other words, the temper carbon, although in a very finely powdered condition, occupies about the same amount of space as an equal weight of graphite, and causes about the same ultimate difference in size between the original pattern and the annealed casting as when gray cast iron is made. An interesting example of this expansion in annealing is shown in Fig. 295, which is a swivel snap for hitching straps. Casting No. 1 is first poured, cooled and cleaned. It is then embedded in the sand of a mold and casting No. 2 is poured around the shank of it, as shown in No. 3 of Fig. 297. Casting No. 2 shrinks



FIGS. 295 TO 297.

upon the shank of No. 1 so as to make a close fit, and no swiveling is possible, but the combined casting is now sent to the annealing-ovens and annealed. This causes the expansion referred to, and as casting No. 2 is larger in diameter, it expands the more, and now turns very easily around the shank of No. 1.

Miscellaneous Iron Products.—In the form of small castings malleable cast iron and similar products often masquerade under the name of steel, because under that name the producer finds a readier market for them. On account of their fluidity they may be cast very cheaply in small sizes, and therefore the temptation to use them as a material for "cast-steel hammers,"[1] "hard-steel" bevel gears, "semi-steel castings," and even automobile "steel" drop-forgings, is a strong one. Engineers are warned to be on their guard against a deception of this kind, for legal redress has been sought many times in vain. It is usual for the manufacturer when putting material of this kind upon the market to qualify the name "steel" with some other letters or name, such as

[1] The trade would ordinarily understand by this name hammers made of crucible steel, so the use of this name is really a fraud.

"P. Q. steel," "Smith steel," etc.; but they all differ from true steel in that they were not "cast into an initially malleable mass." Some are made by melting a large proportion of steel with cast iron, after which the cooled metal may or may not be annealed in iron oxide. Others are made by a long or thorough annealing of ordinary malleable castings in iron oxide, by means of which the metal is decarburized to some depth, and is then carburized again by a cementation process. This makes a very good material for some purposes, such as small bevel gears not requiring strength or much ductility, but it ought not to be called "steel." If the purpose for which it is to be used does not require any other properties than malleable cast iron possesses, then it should be used under its true name; but if it is to be used under circumstances where it is liable to strain, calling it "steel" will not enable it to stand up under the work any better. The confusion is the more easy because genuine steel is made by the cementation of wrought iron, and wrought iron goes in England under the name of malleable iron. In America we seldom call wrought iron "malleable iron," but we often abbreviate malleable cast iron to "malleable iron," or even to "malleable."

Delicate Adjustment of Conditions.—In no metallurgical process must the conditions of chemical composition, furnace work, heating temperatures and lengths of operation be adjusted more delicately than in the manufacture of high-grade malleable cast iron, as may be seen by the following changes that the metal undergoes during the final, i.e., annealing, process, as revealed by the appearance of the fracture. The metal as originally cast will have the so-called *crystalline fracture* of white cast iron, with perhaps a little mottle. This fracture should be changed to a black heart after the annealing process, and the metal will have good strength and ductility. If, however, the composition of the metal was wrong in the first instance, it may quite resist the annealing process and precipitate little or none of its combined[1] carbon. Or else, if the silicon were too high, the castings may have already precipitated too much graphite before the annealing process begins, and the deposition of temper carbon may take place so readily during annealing that the castings will be mushy and lacking in strength.[2]

[1] The term combined is used here to represent carbon in solution or any chemical combination with the metal.

[2] Iron too high in silicon will precipitate too much graphite during its first cooling, and is technically known as low iron; on the other hand, iron with very little silicon is known as high iron.

If, however, the composition of the metal and the melting conditions were correct, a good grade of black heart casting may be produced by a proper anneal, but, should the temperature of annealing be too high, or be continued too long, the black heart fracture may change to a *steely fracture*, showing an iron in which the precipitated carbon has returned to the combined form. Nor is this all; if the annealed castings are cooled too fast after the anneal, or if the black heart castings, after being successfully made, are reheated and hammered, or reheated and quenched in water, the black heart fracture will change to steely. Even the heating to which the finished castings are subjected when they are dipped in spelter for a galvanizing process and then quenched in water, will produce a steely fracture with consequent brittleness if the composition of the metal is not within very narrow limits. There is but one remedy for castings having a steely fracture and that is to re-anneal them and produce the so-called Réaumur or white heart castings. In other words, white heart malleable iron is the end of a series of changes through which the carbon passes during a long annealing process.

Theory of the Black Heart Process.—By referring to the diagram of Fig. 254, suggested by Upton, it will be observed that graphite should normally separate from irons high in carbon during and shortly after solidification. This reaction is avoided in making malleable castings, by cooling the metal rapidly through this range of temperature. The first effect of the annealing process, however, is a slow readjustment of conditions by the occurrence of the reaction which was previously suppressed. That is to say, the carbon is now precipitated within the solid metal. The temperature at which this reaction occurs during the annealing is not as high as the normal temperature for it, but is in the region where cementite (Fe_3C) normally should be produced according to the diagram. If, therefore, the annealing is continued too long, the carbon precipitation is *followed* by its recombination to form the carbide of iron. As the metal is then slowly cooled, this carbide of iron separates and we get the steely fracture, which is characteristic of over-annealed malleable castings.

If, on the other hand, we have obtained a good black heart casting and this is reheated into the region where cementite normally forms, and suddenly cooled, we produce a metal which consists of cementite, mostly dissolved in an iron matrix. This

reasoning fails to explain why the rapid cooling of castings, after a proper annealing, will sometimes produce the steely fracture, and so far as I know, this occasional result yet lacks an explanation.

The reason why cast iron too high in silicon precipitates its carbon too readily and gives a mushy iron is readily explained, since it is known that the presence of silicon will promote the separation of graphite, and especially will make the iron open-grained and cause graphite to separate in larger flakes.

Theory of the Réaumur Process.—In the original Réaumur process the castings are packed in iron oxide during the anneal, and this operation is carried on at a temperature of about 800 to 875° C. (1472 to 1607° F.) for a period of four or five days after reaching full temperature. In the first part of this annealing process conditions are produced which tend to result in black heart castings; then the next step results in conditions that would produce the steely fracture; still the anneal is protracted at the high temperature and, at the end of the 100 hours or so, we have castings in which the white rim of black heart metal extends to the very center—the castings being only 1/2 inch or less in thickness. This white rim, as already explained, is iron from which the carbon has been actually removed bodily, and this decarburization results from a reaction between the iron oxide in contact with the skin of the casting and the carbon in it. Whether the carbon migrates to the surface and is there oxidized by the oxide:

$$3C+Fe_2O_3=3CO+2Fe,$$

or whether oxygen penetrates the metal through its pores in the form of CO gas, or penetrates chemically by forming iron oxide which is acted upon by the carbon:

$$C+FeO=CO+Fe,$$

is a matter on which authorities cannot agree. The first theory is the one which seems to have the preponderance of evidence in its favor. That carbon will migrate in solution is proven in the cementation processes and, at the annealing temperature, the carbon is normally all in solution, whether it be as free carbon, or as carbide. Even the white rim of an ordinary black heart casting contains some carbon in solution.

XIV

THE HEAT TREATMENT OF STEEL

We have already discussed the heat treatment of cast iron under other heads, namely: (1) the rapid cooling from the molten state, or "chilling," and (2) the annealing of malleable cast iron. Heat treatment is of much greater importance in connection with steel, because nearly 99 per cent. of all the steel made is heated either for the purpose of bringing it into the mobile condition in which it can be readily wrought, or for annealing. Indeed, the great majority of steel is heated several times, and some steel is subjected to two or three different kinds of heat treatment.

Improper Heating of Steel

Overheating.—If steel be heated to a high temperature, say 1100° C. (2010° F.), and then cooled (either slowly or rapidly) without being subjected to strain, it will be "coarse-grained" as it is called, that is, its crystals will be relatively large in size. This can be readily seen by breaking it and examining the fracture, which will be bright and sparkling if the crystals are coarse, or dull-looking and fine-grained if they are small (see Fig. 307). The bright fracture is technically called "crystalline" or "fiery," while the fine-grained one is called "silky" or "sappy." The size of the crystals may also be learned with great accuracy by means of the microscope (see Figs. 300 to 305 and 307). Now, if the steel which was coarse-grained after heating to 1100° be heated instead to 1200°, the crystals will be still larger in size; if heated to 1300° they will be larger still, and so on. The size of the crystals will depend first upon which of these high temperatures it was heated to, and second upon the amount of carbon it contains. Low-carbon steel is normally larger in crystal-size than high-carbon steel.

Even the best quality of steel, if rendered coarse-grained by "overheating," will suffer in its valuable properties, and may become quite unfit for use. Medium- and high-carbon steel will lose both strength and ductility; low-carbon steel will lose

strength even up to 50 per cent. of the original, but does not seem to be materially damaged in ductility unless the overheating is continued for a long time or at a very high temperature.

Cure for Overheating.—Let our first example be steel containing 0.9 per cent. carbon, that is, steel consisting entirely of pearlite. If this be heated from some point below the line *P S K* in Fig. 252, page 295, to some point above that line, a new crystallization will occur and will largely obliterate previous crystallization. It seems as if dissolving the ferrite and cementite in each other produces forces which obliterate almost all existing crystalline forms. So, if this particular steel has been made coarse-grained by overheating, we may make that grain fine again by reheating the steel from below the line *P S K* to just above it. This process is known as "restoring," or, by some writers, "refining" the steel. It is an operation which should be thoroughly understood by every metallurgist and engineer. When we reheat the steel we must be careful not to go to a high temperature again, for a new crystal-size is born at the line *P S K*, and the crystals grow with every increase in temperature. The researches of Professors Howe and Sauveur[1] indicate that the size of the crystals is almost directly proportional to the temperature reached above the line *P S K*. If, therefore, we barely cross the line, we will obtain the smallest grain-size that the steel is capable of (see Fig. 307).

The cure for coarse crystallization in steel with less than 0.9 per cent. carbon is to reheat it from below the line *P S K* to above the line *G O S*, at which the last of the ferrite goes into solution. That is to say, the correct temperature for restoring the grain-size will depend upon the amount of carbon in the steel; low-carbon steel must be heated to nearly 900° C. (1650° F.); 0.4 per cent. carbon steel must be heated to nearly 800° C. (1470° F.); and so on.[2] We can never get as small a grain-size in steel with less than 0.9 per cent. carbon as we can in that which is exactly 0.9 per cent. carbon, because a new grain-size begins to grow after we have crossed the line *P S K*, and yet we cannot entirely eliminate the old grain-size until we cross the line *G O S*. Where the lines *G O S* and *P S K* are near together (say, with 0.7 per cent. carbon), the new grain-size does not have much chance to

[1] See page 246 of No. 1, page 8.

[2] It is to be remembered that the changes indicated by the lines in Fig. 252 occur at a higher temperature on heating than on cooling (see page 290); so it is well to heat the steel about 25° C higher than the points on those lines.

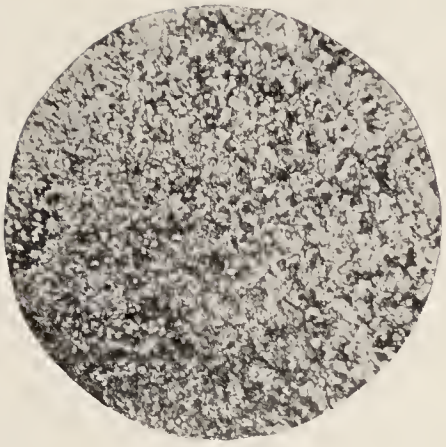


FIG. 300.—NO. 1A. STEEL OF 0.05 PER CENT. CARBON ROLLED.
Magnified 40 diameters.

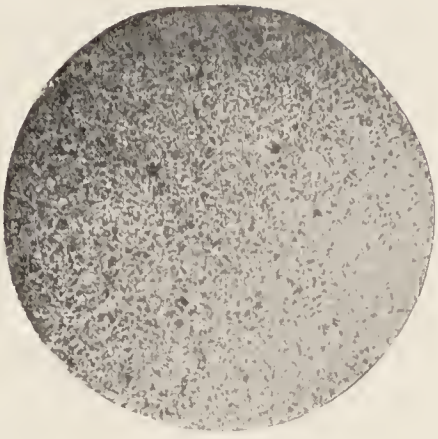


FIG. 301.—NO. 1B. STEEL OF 0.50 PER CENT. CARBON ROLLED.
Magnified 60 diameters.

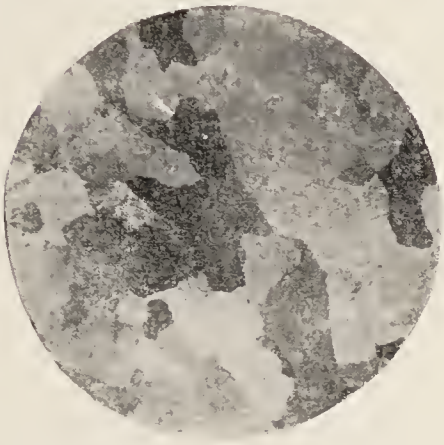


FIG. 302.—NO. 2A. SAMES NO. 1A OVERHEATED TO 1420° C. (2588° F.)
Magnified 60 diameters.

FIG. 303.—NO. 2B. SAME AS NO. 1B OVERHEATED TO 1420° C. (2588° F.)
Magnified 60 diameters.

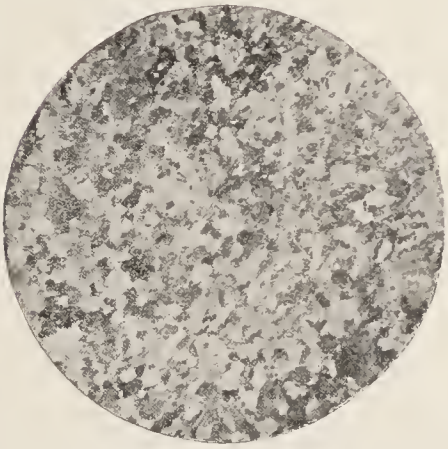


FIG. 304.—NO. 3A. SAME AS NO. 2A. REHEATED SLIGHTLY ABOVE AC_3.
Magnified 40 diameters.

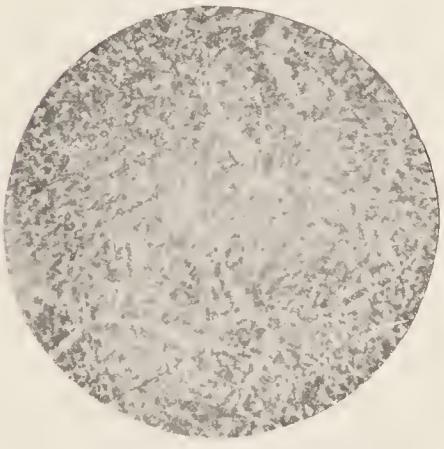


FIG. 305.—NO. 3B. SAME AS NO. 2B. REHEATED SLIGHTLY ABOVE AC_{2-3}.
Magnified 60 diameters.

Series A by F. C. Wallower in the Metallographic Laboratory of Columbia University, Department of Metallurgy.

Series B by G. Rocour in the Metallographic Laboratory of Columbia University, Department of Metallurgy.

grow before the restoration is complete, and therefore we may obtain steel with a pretty small grain; but where they are far apart (as in the low-carbon steels) the restoration can never be very thorough, because we have to go so far above *P S K* to obliterate the old grain-size that the new grain-size will have attained ample proportions. But the evidence seems to show that the best net result is obtained by going just above the line *G O S* in all cases.

In the case of steel with more than 0.9 per cent. carbon a somewhat similar condition exists: we must reheat the steel above the line *S a* in order to produce complete elimination of the previous grain-size but a new grain-size begins to grow from the crossing of the line *P S K*. But here we disregard the line *S a*, and restore our steels in every case by reheating them over the line *P S K*, just as in the case of pure pearlite. The reason for this is that the lines *S a* and *P S K* diverge so rapidly that we have to heat very far above the line *P S K* before we cross *S a*, and therefore the new grain-size has grown greatly. Furthermore, the only object of heating above the line *S a* is to take the excess cementite into solution; for the ferrite and cementite in the pearlite all went into solution as sood as we crossed the line *P S K*, but the amount of excess cementite is always small in proportion, and therefore in its influence on restoration. Even with steel containing 2 per cent. of carbon the excess cementite is only 16 per cent. This is different from the low-carbon steels, where the excess ferrite will be usually over 80 per cent.

Evidence of Overheating.—A piece of steel may be heated many times above the line *P S K* and cooled again, but obviously only the latest heating will leave its impression on the structure, because each crossing of the line on the way up removes the effect of previous heat treatment.[1] The relation between the size of the crystals and the temperature above *P S K* is so constant that we may determine what this temperature was from the analysis of the steel and an examination of the grain. To do this it is usually necessary to get a piece of steel of the same analysis, heat different pieces of it to various temperatures, and compare

[1] This is only true in a qualified sense, in that the previous overheating must not have been very close to the melting-point. We shall discuss this point under the head of "Burning." Indeed, even where burning has not occurred, a skillful microscopist may sometimes discern the effect of over-heating after the steel has been restored by reheating; because, although the crystals are all small, they are arranged in groups which show the form of the previous large crystals.

(see page 367). The analysis must be approximately the same not only in carbon but also in phosphorus, sulphur, silicon, and manganese, as well as in any alloying elements, if present, such as nickel, chromium, tungsten, etc., because all of them have an effect upon the size of grain and also upon the change in size of grain by overheating. Generally, it is not important to know the exact temperature of overheating, but only whether or not overheating in some degree has occurred; and this is not difficult to prove, because almost all who use steel are familiar with the normal fracture of steels of different carbon and can tell at a glance if the grain is large; those who are not so familiar with its appearance may easily become so. The grain being large is proof that overheating was the cause, provided chemical analysis shows everything about normal, especially phosphorus and silicon.

Steel members of bridges or other structures sometimes break and disclose a crystalline fracture which is often attributed to the effect of vibration. The same thing occurs with points or shanks of rock drills and similar implements. It is the more general opinion among metallurgists that the crystalline fracture in all these cases is due to faulty heat treatment during manufacture, and especially to finishing the forging or rolling while the temperature is still too high. The manufacturers of steel like to maintain the opposite opinion, for obvious reasons, but I do not know of there ever having been any reliable proof offered that vibration had caused, or is capable of causing, large-sized grain in steel. It may be possible, but the more we learn about the subject the more we are inclined to believe that improper manufacture is the cause, and that the grain was large before the steel was put in service, although its nature was not disclosed until the break occurred.

Mechanical Cure for Overheating.—When steel is to be rolled or forged it is frequently heated to a temperature of 1100° to 1350° C. (2010° to 2460° F.), and it might be thought that this treatment would seriously damage it. So it would, but for the circumstance that the subsequent mechanical pressure upon the metal breaks down the crystals and reduces them to a small size. The result is that the final size of the crystals is dependent upon the temperature of the material at the finish of the mechanical operation. In other words, steel finished at 900° C. (1650° F.) has a finer structure than the same steel finished at 1100° C. (2010° F.). We do not feel warranted in stating numerically the

exact relation between the finishing temperature and the grain-size, as we have not yet sufficient evidence, but several rules affecting the final size of grain seem to be virtually established: (1) It is more advantageous to have the mechanical work applied continuously from the highest temperature employed down to the finishing temperature, rather than to have long waits during which the steel cools; and especially is this true when the amount of work put upon the metal at the lower temperature is small. In other words, if the steel is formed roughly to shape and size at a high heat, is then allowed to cool, and a little work is done upon it at the lower temperature, the grain will not be its best. (2) It is best for the metal to be worked by several passes through the rolls, or many blows of the hammer, rather than to effect the same amount of reduction by a lesser number of heavy drafts. (3) The greater the amount of reduction the better; that is, to work a large piece down to the desired article gives a better structure. (4) The best temperature at which to finish the work is probably upon, or slightly below, the lines *G-O-S* or *S-K* in Fig. 252, page 295.

Action in Rolling.—The exact crystalline action that takes place under mechanical treatment in not definitely known. In the case of rolling Professor Howe has tentatively assumed the conditions graphically shown in Fig. 306,[1] in which the line *D G* represents the size of grain at the different temperatures. At 1400° C. (2550° F.) the grain-size is represented by the distance of the line from the axis *O-O*. On the first passage through the rolls the grains are crushed to a very small size, but on emerging again they grow very rapidly. Meanwhile, however, the metal has been cooled, and this fact, as well as the inability of the grains to grow instantly, causes the new size of grain to be smaller than before. Therefore, each passage through the rolls renders the crystals smaller in size, the final size depending upon the temperature and the amount of pressure in the last pass. The only abnormal assumption in this argument is that the crystals grow rapidly after the crushing, whereas we know that when steel is heated to any of these high temperatures, the growth is relatively slow. This objection is not strong enough alone to refute the theory, but other hypotheses may be advanced for those who require further explanation. For example, it may be supposed that the steel is so mobile at the very high temperatures that it

[1] Page 263 of No. 1.

yields to distortion, not altogether by the crushing of the crystals, but by the sliding of the crystals past one another; as the temperature becomes lower, however, the mobility of the mass becomes less, and less sliding is possible, so that more crushing of the crystals takes place.

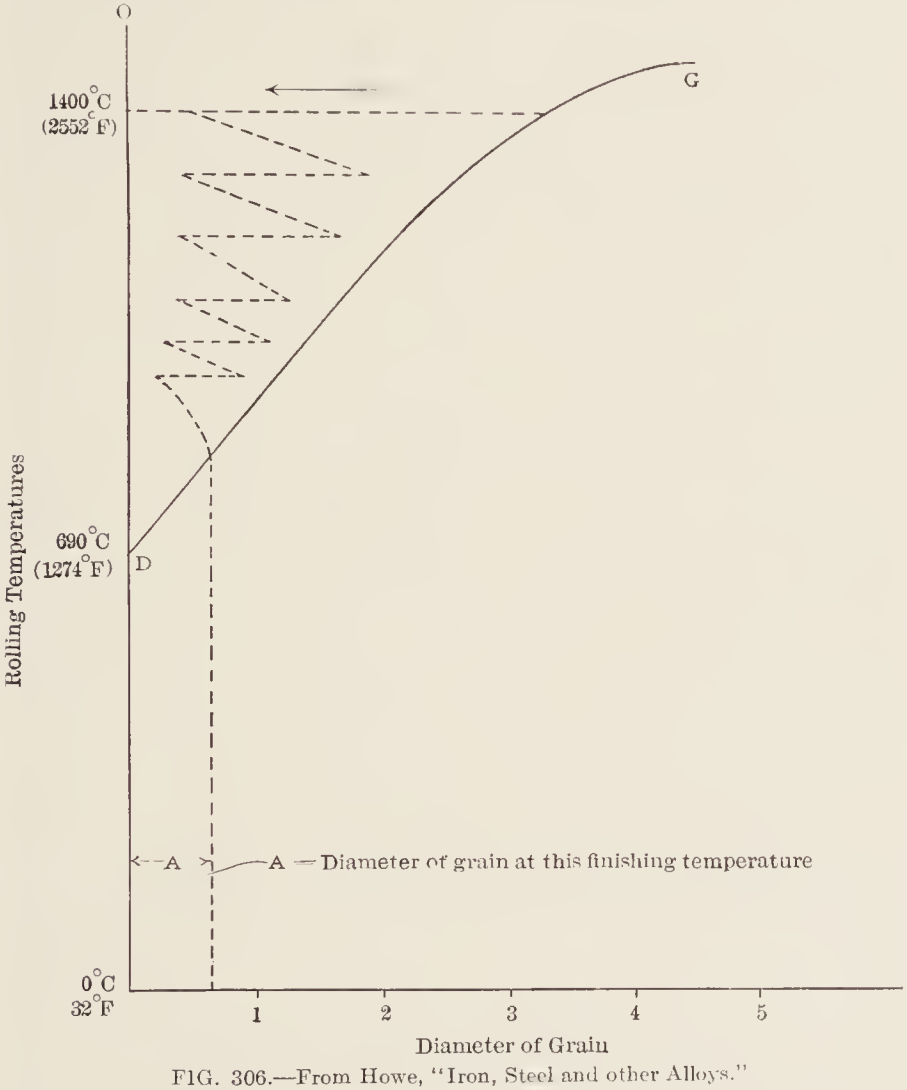


FIG. 306.—From Howe, "Iron, Steel and other Alloys."

Finishing Temperatures.—William Campbell has studied the finishing temperature of steel containing 0.5 per cent. carbon and finds that the very best qualities are produced in the steel if mechanical work is ended just at the time when ferrite begins to separate from solid solution, that is to say, just when the steel is below the line *G-O-S* in Fig. 252, page 295. Work below that temperature greatly increases the brittleness of the material,

while finishing the work at a higher heat results in lower strength. Upon the evidence at hand, we may tentatively assume like conditions for steels of any carbon, and expect the best results if mechanical work is ended when the steel is at a temperature which brings it exactly upon the line *G-O-S* or *S-K*, but reserving, perhaps, the right to change this statement slightly when more data are obtained.

Welding.—This brings us to the subject of welding, or the joining of two pieces of wrought iron or steel by pressing or hammering them together while at a very high temperature. In this way a joint may be made which cannot be seen by the eye unless the steel is polished and etched with acid, which usually develops the junction line very clearly. The exact temperature of welding is not known, but probably it is very near the melting-point, where the steel is in a soft and almost pasty condition. Low-carbon steel welds most easily; moreover, all impurities, especially silicon and sulphur, reduce weldability. The procedure in welding is very simple, and consists in heating the two pieces that are to be welded to a high temperature, dissolving off the iron oxide, and then pressing the two pieces together forcibly. The dissolving off of the oxide is usually accomplished by rubbing the metal in some flux, such as borax. At the present time various patented "welding plates" are sold. These consist of thin plates of flux which are put between the two pieces to be welded and so get rid of the oxide, the pieces being hammered together with the plate between them.

In the actual manipulation for welding the two pieces that are to be joined together are usually "upset," or in some way enlarged in size, so that after the junction the part of the bar right at the weld is larger in size than the remainder. This part is then hammered continuously until the metal is at a red heat, the object being to break up the coarse crystals produced by the high temperature, and, by having a low "finishing temperature," to obtain a small grain-size. With proper welding this object will be attained so far as the metal immediately adjacent to the weld is concerned, but there is always a spot within six inches or so of the weld which must necessarily have been overheated without subsequently receiving mechanical treatment, i.e., "hammer refining," down to the proper finishing temperature. Thus it is that most welded pieces break at a point not far from the junction and under a strain much less than the original strength

of the bar. Blacksmiths and experienced welders are wont to declare that if a welded bar does not break in the weld itself, then it must be as strong as the original metal. However, this is by no means true. In a welding test carried on with great care in this country by skillful and experienced welders who were placed upon their mettle,[1] the strength and elastic limit of the welded bar was almost never as great as the original bar, and in some cases was less than half. In ductility even worse results were obtained. In a similar test carried on at the Royal Prussian Testing Institute the average strength of welded bars of medium steel was only 58 per cent. of the original, that of softer steel only 71 per cent., and of puddled iron only 81 per cent., while the poorest results were only 23, 33, and 62 per cent. respectively. It was seen that bad crystallization adjacent to the weld was the cause of the damage.

Welded steel and iron bars should therefore always be reheated after cooling to a temperature just above the line *G-O-S*, in order to restore by heating the grain-size of all parts.

Burning.—In the vernacular of the trade, all overheated steel is termed "burnt," but this is not correct usage, because true burning takes place only when the overheating is most abusive, and, indeed, when the metal is heated almost to its melting-point. It is probable that steel is burnt only when it is heated above the line *A-a* in Fig. 252, page 295. Alfred Stansfield has studied this question very ably,[2] and distinguishes three stages of burning. The first stage is reached when the steel barely crosses the line *A-a*, that is, when the first drops of melted metal begin to form in the interior of the mass. They segregate to the joints between the crystals and cause weakness. Stansfield thinks that steel burned only to this stage may be restored by reheating it first to a high temperature, cooling, and then heating again to a temperature just above the lines *G-O-S-K*. The second stage in burning is reached when these liquid drops segregate as far as the exterior and leave behind a cavity filled with gas. Stansfield thinks that steel burned to this stage might be restored by combined reheating and forging. As a matter of safety, however, I believe it would be well to remelt all such material; in other words, send it to the scrap pile. The third and last stage of burning is reached when gas collects in the interior

[1] See pages 401 to 406 of No. 2.
[2] See No. 143,

of the metal under sufficient pressure to break through the skin and project liquid steel, which produces the well-known scintillating effect at this temperature. Into the openings formed by these minute explosions air enters and oxidizes the interior. There can be no remedying of steel which has been burned to this extent.

Metcalf Test.—A very interesting experiment is the "Metcalf test," originated by William Metcalf.[1] It is best performed upon a bar of high-carbon steel, because this material shows the

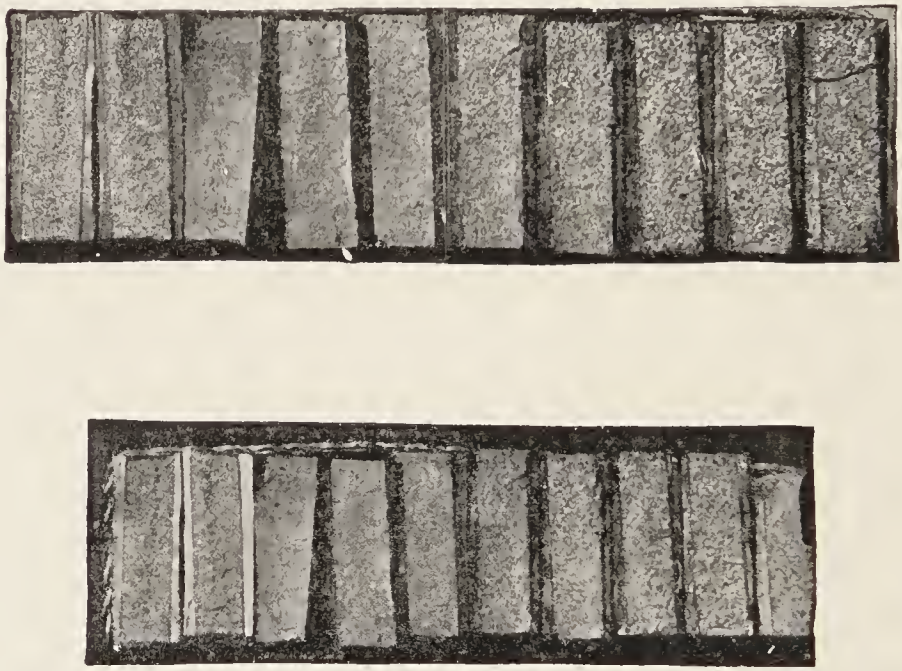


FIG. 307-308.—METCALF TEST. FRACTURES OF STEEL CONTAINING ONE PER CENT. OF CARBON.

differences in structure so readily to the eye. A bar of steel about 12 in. long is notched with a hacksaw or chisel at intervals of an inch. One end is then placed in a fire and heated to a temperature at which it scintillates, while the other end is at a black heat. Then it is removed and cooled. It is immaterial whether the cooling be rapid or slow, but time may be saved by plunging it into water. It is then broken at every notch, and an examination of the fractures will show a very large size of crystals at the end which is burnt, gradually decreasing until a fine and silky appearance is presented where the metal was exactly at

[1] See pp. 405, 406 (especially 406) of No. 116.

the temperature of restoration, while beyond that point the fracture will be the same as that of the original bar. In case this test is made upon low-carbon steel it should not be notched before treatment, but afterwards it should be cut apart with a hacksaw at intervals of an inch, and then polished and examined under the microscope, because soft steel will not break without bending, and this bending destroys the indications of the fracture. This Metcalf test is very serviceable in case we desire to compare one steel, suspected of being overheated, with another of like analysis, to determine the degree of overheating.

Castings do not Burn.—It might be thought that every steel casting would suffer the injuries due to burning because it is cooled through the space between the lines *A-B* and *A-a*. Such injury, however, does not ordinarily take place, and this fortunate circumstance is explained in part by each of three differences existing between the heating and cooling of steel: (1) When steel is heated into the area where burning takes place, it is subjected longer to the burning temperature, because it generally takes longer to heat steel than to cool it. (2) When steel is being heated, the heat is traveling inward from the outside, and therefore all parts are expanding, and there is some opportunity for the crystals to draw apart and form cavities. On the other hand, when it is cooling from the molten state, the outside layers are the cooler, and tend to contract upon the interior and hold the crystals more firmly together, as well as preventing drops oozing out. (3) When steel is cooling from a molten state, it is constantly giving off from solution hydrogen and other deoxidizing gases which are soluble in it while liquid, and these gases prevent the oxidation of the crystal faces by the percolation of air into the interior.

Ingotism.—I have already discussed ingotism and said that the crystals in cast steel are larger than those of rolled steel, due to growth while the metal is at a high temperature, and I have stated that sometimes these crystals are very large, because the conditions of casting cause the steel to occupy a longer time in cooling from the liquid state down to a black heat. It is probable that ingots and castings do not show the effects of ingotism to any marked extent unless they are a long time above 1100° C. (2010° F.). In case these coarse crystals do form, they may be restored to some extent by reheating the casting to a point just above the line *G-O-S*.

Stead's Brittleness.—In addition to the damage caused by overheating, steel very low in carbon (say under 0.15 per cent.) is subject to another and peculiar danger, for if this soft steel be held for a very long time at temperatures between 500° and 750° C. (930° and 1380° F.), the crystals become enormous and the steel loses a large part of its strength and ductility. Fortunately it takes a very long time, in fact days, to produce this effect to any alarming degree, so that it is not liable to occur, even through carelessness, during manufacture or mechanical treatment. But steel is sometimes placed in positions where it may suffer this injury, for example, in the case of the tie-rods of furnaces, supports for boilers, etc., so that the danger should be borne in mind by all engineers and users of steel. I recall an instance where the breaking of a piece of chain that supported one side of a 50-ton open-hearth ladle caused a loss of life under the most horrifying conditions, due to the fact that the wrought-iron chain had been heated up many times to a temperature above 500° C. (930° F.), and had finally reached a condition of coarse crystallization, so that it was unable to bear the strain upon it when the ladle was full of metal.

This phenomenon of coarse crystallization in low-carbon steel is known as "Stead's brittleness," after J. E. Stead, who has explained its cause. The effect seems to begin at a temperature of about 500° C., and proceeds more and more rapidly with an increase in temperature until we reach 750° C., above which no growth seems to take place. The damage may be repaired completely by heating the steel just above the line *G-O*. In other words, the remedy for coarse crystallization in this case is the same as that for coarse crystallization due to overheating, and all steel which is placed in positions where it is liable to reach these temperatures frequently, should be restored at intervals of a week or a month, or as often as may be necessary.

Hardening of Steel

If steel be raised to a bright-red heat and then rapidly cooled, as, for example, by plunging it into water, it becomes very much harder and at the same time stronger and more brittle. One circumstance is absolutely necessary to produce the increase in hardness, namely, that the temperature from which rapid cooling takes place shall be above the critical temperature of the steel.

Take, for example, steel containing 0.9 per cent. carbon; we may heat this ever so little below the point *S* in Fig. 252, page 295, and no increase in hardness will take place, even though we cool with extreme rapidity. On the other hand, if we cool the same steel rapidly from ever so little above the point *S*, it will be hard enough to scratch glass and brittle enough to fly into pieces under a blow of the hammer. This is the maximum practical hardness which can be obtained in this steel for if we quench it at a higher temperature, the only result of importance is to damage it by increase in grain-size. In case we have less than 0.9 per cent. carbon in our steel, the best temperature for hardening is just above the line *G-O-S*, because that gives the maximum hardness and also the best grain-size. The best temperature from which to harden steel with more than 0.9 per cent. carbon is just above the line *S-K*, because that gives the best grain structure, although it is true that greater hardness is obtained if we cool from above the line *S-a*.

Carbon and Hardness.—The hardness of steel increases with every increase of carbon. This applies to the hardness of steel in its natural state, and still more appropriately to its harness after heat treatment. Although iron free from carbon is hardened by rapidly cooling from above the point Ac_2 (760°C. = 1400° F.), and a little more so when rapidly cooled from above Ac_3 (900° C. = 1650° F.), yet this degree of hardness is so slight as to be perceptible only by means of delicate laboratory tests. With 0.25 per cent. carbon the hardness begins to be perceptible by crude tests, but it is only when we get above 0.75 per cent. carbon that ordinary steel acquires sufficient hardness for the process to be used commercially—for example, for springs, saws, etc. Metal-cutting tools are usually made of steel containing 1 per cent. or so of carbon, while very hard implements, such as files, etc., will contain 1.5 per cent. or slightly more.

Rate of Cooling and Hardness.—The degree of hardness of steel also varies with the speed of cooling from above the critical range of temperature. When the cooling is very slow, as, for example, when it takes several days to cool, the steel will be as soft as it is possible to make it. When it is cooled by being taken out of the furnace and suspended in the air, or thrown upon a sand floor, it will still be relatively soft. When cooling is still more rapid, as, for example, when it is taken out of the furnace at a bright-red heat and plunged into a heavy oil with a low conduct-

ing power for heat, it becomes quite hard and springy, provided its carbon is in the neighborhood of 0.8 per cent. or above. Quenching in a thin oil from the same temperature makes it still harder. Quenching in water makes it harder still; and so on, the degree of hardness increasing as we quench in liquids which take the heat away from it faster and faster, such as ice-water, ice-brine, ice-sodium chloride solution, and mercury near its freezing-point (–39° C. = –38° F.).

THE EFFECT OF CARBON ON THE MECHANICAL PROPERTIES OF STEEL AFTER HARDENING IS SHOWN BELOW:[1]

Carbon per cent.	Tensile strength in soft state			Tensile strength when hardened.		
	Ultimate lbs. per sq.in.	Elastic limit lbs. per sq. in.	Elongation in 2″-per cent.	Ultimate lbs. per sq. in.	Elastic limit lbs. per sq. in.	Elongation in 2″-per cent.
0.10	60,300	36,300	29	66,400[2]	40,300	24
0.14	61,500	35,200	27	73,100[2]	39,600	22
0.23	66,500	41,200	26	99,400[2]	54,000	14
0.52	97,800	52,600	20	132,100	81,400	9
0.60	116,400	66,500	14	153,400	102,100	4
0.72	130,700	75,800	9	180,100	105,500	0

Theories of Hardening.—One essential feature of hardening is that the steel must be heated to a temperature above the line *P-S-K*, that is to say, to a point where at least some of the solid solution of iron and carbon is formed. There are several different theories to explain the hardness produced by rapid cooling from this point, the two most important being the "carbon theory" and the "allotropic theory." Both of these theories depend upon the following line of reasoning: At temperatures above the critical range the molecules of steel are in a hard condition.[3] As they cool from this point and cross the critical range of temperature, the molecules change from the hard state to a soft state, but this

[1] See No. 149.

[2] The increase in strength in these soft steels is due in large part to the finer size of grain produced by rapid cooling through the critical range.

[3] It is difficult for some to understand how molecules of steel can be in a hard condition at a temperature at which we know that the mass as a whole is soft and mobile; but this can be explained by the following comparison: A ball of wet sand and clay is soft and mobile as a whole, because the particles move by each other readily and the mass changes its shape under pressure; yet the individual particles composing this mass are many of them hard enough to scratch glass with ease.

change is not rapid and requires time for its accomplishment; rapid cooling does not afford the necessary time, and so perpetuates the hard state of the molecules. This line of reasoning leaves only one point in doubt, namely, what causes the molecules to be hard when the steel is above the critical temperature, i.e., when iron and carbon are dissolved in each other?

The Carbon Theory.—The carbon theory assumes that the hardness of steel is due altogether to the carbon dissolved in it, and in evidence its advocates point to the extreme hardness of one form of carbon—the diamond. This theory has the advantage of simplicity, and has in its favor the fact that the hardness varies almost directly with the amount of carbon. Against the theory, it is urged that the amount of carbon is really too small to produce such a great degree of hardness in the whole mass of metal. Furthermore, although carbon is found in many metals it does not confer hardness on any of them except iron.

The Allotropic Theory.—We have already learned that in the solid solution the iron is present in the gamma allotropic form, and the majority of metallurgists attribute the hardness of steel to the allotropic form, and deny that carbon is the sole factor. It has been shown, by very delicate laboratory tests on iron practically free from carbon, that the gamma and beta allotropic modifications are harder than the alpha modification. These did not show how great was the increase of hardness of one form over another, because it was not possible to cool the iron fast enough to prevent it changing back in part to the alpha form. In the absence of carbon the change from gamma to beta and from beta to alpha is very rapid, so that cooling has to be almost instantaneous in order to prevent it, and this, of course, is impossible. The "allotropists" explain the greater hardness of high-carbon steel as compared with low-carbon steel upon the basis that the presence of carbon makes the change from gamma to beta and to alpha iron slower, and therefore enables more of the iron to be retained in the gamma and beta forms by the rapid cooling.

An additional argument in favor of the allotropic theory is that when steel cools slowly through the critical range, it loses its hardness slightly before the carbon comes out of solution. This would indicate that the allotropic change took place before the carbon change, and that the allotropic change was the cause of hardness. What is true of the loss of hardness is also true to the other physical changes which take place at the same time.

That is to say, the steel regains its magnetism, decreases in electric resistance, and increases in thermo-electric power in a large part before much carbon is separated from the solution.

The Compromise Theory.—Several theories have been advanced which are a compromise between that of "the carbonists" and that of "the allotropists." The simplest of these, and the theory now most generally accepted, is that the hardness of the molecules of steel above the critical range is due partly to the allotropic form in which the iron exists, and partly to the fact that we have a solid solution of iron and carbon.[1] In other words, the hardness is due to the fact that we have a solid solution of carbon in an allotropic form of iron.

Tempering.—Hardened steel is too brittle to be used without some degree of tempering, except for a small variety of purposes, such as the points of armor-piercing projectiles, the face of armor plate, etc. In order to understand just what tempering does, let us consider the exact condition of hardened steel: it is in a hard and brittle condition which is not natural to it at atmospheric temperatures, but which has been brought down with it from a higher temperature by means of rapid cooling. Theoretically, when the temperature fell below 690° C. (1272° F.), the molecules of steel should have changed over to the soft form. Their hard condition is not in equilibrium at the lower temperature, in the same sense that ice is not in equilibrium in hot weather. Why, then, does not the steel change back into the soft form? Ice, if given time enough, will all change into water when the temperature is above 0° C. (32° F.). The reason the change does not take place in the steel after we have cooled it to the atmospheric temperature is that the mass as a whole becomes too rigid and immobile at the lower temperature to permit any alteration in its molecules to take place.

However, it is only necessary to decrease this rigidity in order to permit a slight change. For example, if a piece of hardened steel be kept in boiling water for some days it will lose a part of its hardness; if it be heated a little more, it will lose more hardness and lose it much more quickly. Each loss in hardness is accom-

[1] Where I speak of a solution of carbon and iron. I intend to include under this also the solution of iron and a carbide of iron. That is to say, we have two substances, iron and carbon, and they are dissolved in each other. It may be that the carbon is united with part of the iron to form a carbide, and then that this carbide is dissolved in the rest of the iron; but I use the term "solid solution of iron and carbon" to cover either this condition or that of elemental carbon dissolved in iron.

panied by a loss in brittleness as well. If it be heated to about 200° C. (392° F.), quite a little of the brittleness will be lost and a part of the hardness.[1] It is now in condition to be used for steel engraving tools, lathe tools, and other implements to cut metals. If we heat to 250° C. (480° F.), we temper still further, and so on.

It is interesting to note that when hardened steel is tempered, the physical changes produced by the tempering—the decrease in hardness and brittleness, increase in electric conductivity, etc. —precede the separation of carbon from the solid solution. By tempering we may lose 70 per cent. of the hardness, 93 per cent. of the electric resistance, and nearly 100 per cent. of the thermo-electric power produced in the steel by the hardening operation, when only 13 per cent. of the carbon has been changed from the dissolved form.[2]

Hardening, Tempering, and Annealing.—Only quenching in water, or in some other medium which takes the heat away as fast or faster, goes under the name of hardening. Quenching in heavy oil, melted lead, etc., cools the steel less rapidly, and makes it less hard and less brittle than quenching in water, so to this operation the name of "tempering" is given. Cooling in the air, in sand, in the furnace, or by any other slow method, is called "annealing."

Magnetism and the Lines G-O-S-K.—It will be remembered that iron is present in the solid solution in the gamma allotropic form, and therefore the solid solution is non-magnetic. Therefore all the steels to the right of the point *O* in Fig. 252, page 295, lose the last of their magnetism at the same time as they cross the lines *O-S-K*. These steels comprise all containing 0.4 per cent. of carbon and more. To harden, anneal, or restore such steels we may guide our work of heating by means of an ordinary horse-shoe magnet, which makes a most accurate and simple tool. Let the magnet hang outside of the furnace and take a sample of steel out at intervals to test it. When it no longer attracts the magnet, begin to cool it. For steels with less than 0.4 per cent. carbon we can use the magnet to tell us when the temperature corresponding to the line *M-O* is reached, for all iron loses its magnetism at that point, and then it is a comparatively simple matter to judge by eye the relatively short temperature intervals

[1] After the heating it is immaterial whether cooling is fast or slow, as the same result will be produced.

[2] See footnote, page 302.

above that point which it is necessary for the steel to traverse before it crosses the line *G-O*. If this method is followed I think it will be found in many works that annealing temperatures have been much too high, and that better steel will be obtained in future. We do not get the steel any softer by annealing it hotter, but only by slower cooling from the correct temperature.

The Constituents of Hardened and Tempered Steels

It is now pretty generally admitted by metallurgists that austenite is the solid solution of gamma iron and carbon. When this cools slowly through the critical range it decomposes into ferrite and cementite. It is also very generally admitted that the decomposition does not take place spasmodically, but progresses by stages, and many believe that the substances identified under the microscope as martensite, troostite, and sorbite are the products of these stages. That is to say, martensite is the first stage of decomposition of austenite, troostite is the second, sorbite is the third, and pearlite is the consummation. If this is so, then austenite will be found in the steels cooled with the greatest rapidity, martensite will be found in those cooled with the next degree of rapidity, troostite will be found in the next intermediate steels, sorbite in the next, and pearlite in those slowly cooled. To this extent, indeed, the facts agree with the argument, but hardly any dare predicate further too positively from this evidence alone. Our knowledge upon this whole subject is still very new, and though a small army of workers is busy collecting evidence and interpreting it as best they can, all our present statements must necessarily be made tentatively, with the idea of presenting the facts so that they may be of some practical benefit, even though later information may oblige us to change slightly the scientific basis upon which we found them.

Austenite.—Austenite can be obtained at atmospheric temperatures in ordinary carbon steels only when three conditions are collectively present: (1) The brake action of carbon must be very strong, that is, there must be above 1.1 per cent. of carbon present; (2) the steel must be cooled with the greatest rapidity, as by quenching it in iced solutions at, or a few degrees below, zero C.; and (3) it must be cooled from above 1000° C. (1830° F.). Even then austenite cannot be preserved throughout the whole mass of the steel, but at least a part of it will be decomposed to

the stage represented by the martensite structure (see Fig. 312) while cementite will separate also if the carbon is very high. Under the microscope austenite may be differentiated from martensite by its white color after etching with a 10-per-cent. solution of hydrochloric acid. Better results are obtained if the etching is aided by electrolysis, the steel being made the anode, or positive pole, and a piece of platinum being made the cathode. Austenite does not occur often in cold commercial carbon steels, but is found frequently in alloy steels.

Martensite.—Martensite is the chief constituent of ordinary hardened steels, that is, of steels quenched from above the critical range in water or in an iced solution. Its structure is shown in Fig. 312. It is even harder than austenite, for a steel needle drawn across the surface of a polished piece of steel will scratch the austenite plainly without making a mark upon the martensite. Its structure is developed by the "polish attack" method of F. Osmond (see p. 447). Martensite is also found very largely in the tempered steels, to which they doubtless owe their quality of hardness. It was long thought to be the solid solution itself, and is still spoken of as such in several books upon the subject; but the microscope shows positively that it is not free from some decomposition.

Hardenite.—Hardenite is the name sometimes given to "saturated martensite," that is, martensite containing 0.9 per cent. carbon. It is often found in German and French, and occasionally in English and American books.

Troostite.—Troostite is obtained in either of three ways: (1) By quenching steel in water when it has cooled just to the line *P-S-K* in Fig. 252, page 295; (2) by quenching steel from a higher temperature in boiling water, oil, or some other of the tempering mediums; and (3) by hardening in the usual way and then tempering by reheating. In other words, troostite is a product of the usual tempering operations, and is found abundantly in tempered steels. Under the microscope it may be distinguished by the "polish attack" (page 447) or by etching with tincture of iodine. It appears as yellow, brown, blue, or black colorations on the borders of the martensite, and often between the martensite and sorbite. The division between it and the martensite is very sharp, but it shades very gradually into the sorbite (Figs. 314, 315).

Sorbite.—Sorbite is very close to pearlite, and differs from it chiefly in that the crystals of ferrite and cementite are not quite

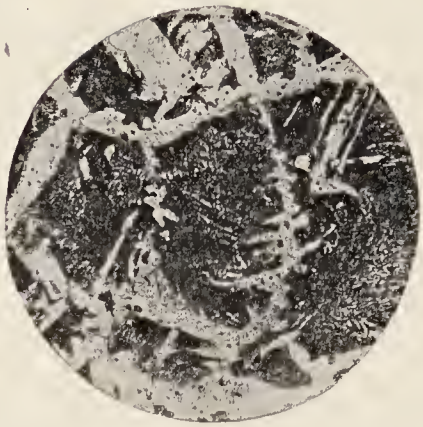


FIG. 309.—NO. 1A. STEEL OF 0.34 PER CENT. CARBON OVERHEATED TO ABOUT 1300° C. (2372° F.)
Magnified 250 diameters.

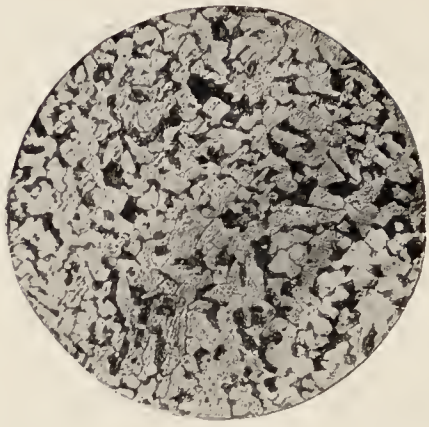


FIG. 310.—NO. 2A. SAME AS NO. 1A REHEATED SLIGHTLY ABOVE AC_3
Magnified 250 diameters.

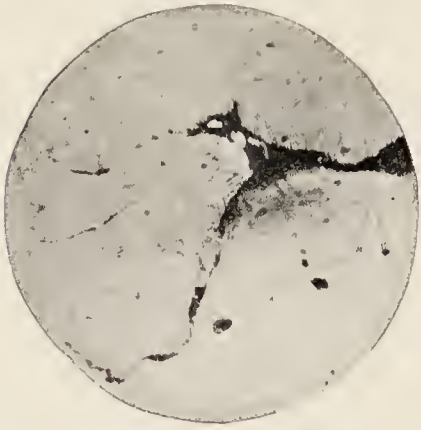


FIG. 311.—STEEL OF 1 PER CENT. CARBON BURNT.
Magnified 265 diameters.

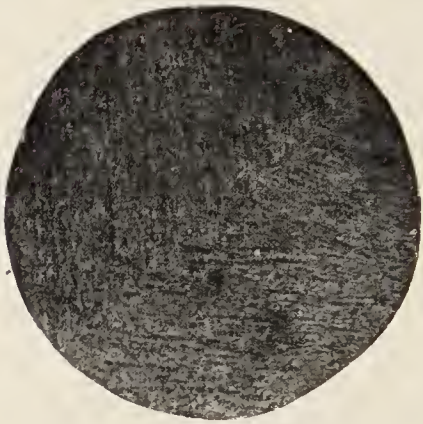


FIG. 312.—MARTENSITE.
Magnified 250 diameters.

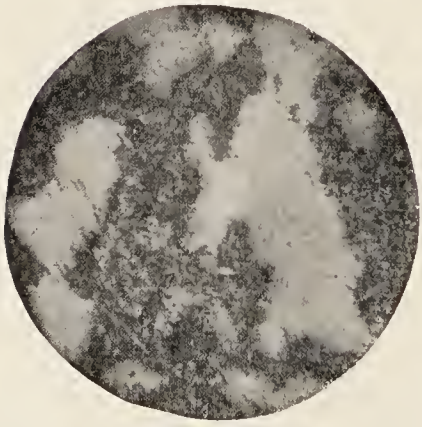


FIG. 313.—MARTENSITE (WHITE) AND TROOSTITE (DARK).
Magnified 500 diameters. Etched lightly with tincture of iodine. (H. C. Boynton.)

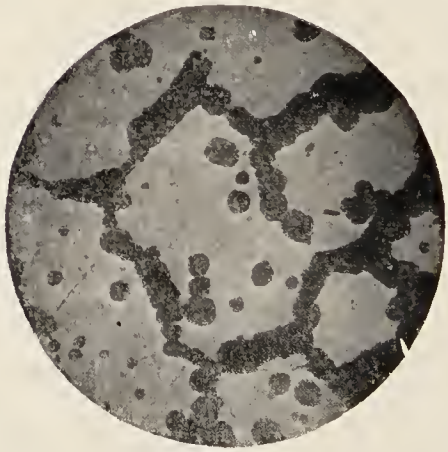


FIG. 314.—AUSTENITE (WHITE) AND TROOSTITE (DARK).
Magnified 60 diameters. Steel of 1.41 per cent. carbon. Etched with picric acid. (William Campbell.)

perfectly developed and segregated from one another (see Fig. 315). It might at first seem almost like splitting hairs to differentiate between the two, but this is not so, because of the importance of sorbite, due to its having greater strength than pearlite. Pearlite has a finer and more intimately entangled structure than any other slowly cooled steel, and to this we attribute the fact that pure pearlite steel (0.9 per cent. carbon) is stronger than any of them. But the structure of sorbite is even finer than that of pearlite, and sorbitic steels are correspondingly stronger than pearlitic steels.

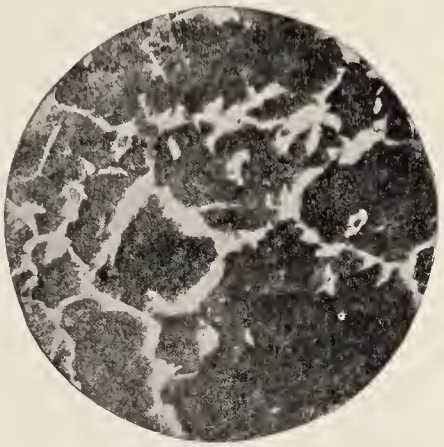


FIG. 315.—FERRITE AND SORBITE IN RAIL STEEL.
Magnified 250 diameters. Etched with picric acid.

Sorbite may be obtained by quenching the steel immediately below, or just at the end, of cooling through the critical range, or by cooling the steel pretty fast through the critical range without actually quenching, or by rapid cooling and then reheating to about 600° C. (1110° F.).

Osmondite.—Only very recently what is apparently another constituent of hardened and tempered steels has been discovered, and to this the name of "osmondite" has been given. It would seem that osmondite is a solid solution of carbon (or of a carbide of iron) in the alpha allotropic modification of iron. It is therefore an anomaly, and can only exist in equilibrium momentarily, so to speak, because the normal solid solution contains the iron in the gamma allotropic form. It would seem, however, that when this gamma solid solution decomposes, it passes through a phase wherein the iron has changed from the gamma to the alpha form, before the precipitation of the ferrite occurs. In other words, then, osmondite is simply another stage in the decomposition of austenite into pearlite. It differs from the other stages by having a definite constitution and nature, whereas martensite, troostite, and sorbite are more or less indefinite and uncertain in composition, being in fact probably a mixture of two or more constituents rather than definite and individual components.

It is evident that osmondite can never compose the whole of

any piece of steel, because the earlier stages of the austenite decomposition will grade into it on the one side and the later stages on the other. That is to say, we would not expect that the entire piece of steel would change simultaneously and instantaneously from austenite into osmondite, and then likewise from osmondite to pearlite. Osmondite may be obtained by tempering hardened steel at 400° C. (750° F.), but a method of distinguishing it under the microscope is not known at present. Our chief means of recognizing it are by the fact that it causes the steel to dissolve more rapidly in dilute sulphuric acid and to be colored more deeply by alcoholic hydrochloric acid, and by the fact that steel containing a good deal of osmondite has lost a major part of all the qualities given to it by hardening, although almost all the carbon is still in the solid solution.

It is to be noted that the evidence proving the existence of osmondite is still open to the possibility of doubt, although the probabilities are greatly in favor of it.

Summary.—We may summarize the constituents of hardened and tempered steels in the following table, which is adapted from one designed by Howe:

STAGES OF THE TRANSFORMATION FROM AUSTENITE INTO PEARLITE

Name	Constitution
Austenite	Solid solution of an iron carbide in gamma iron.
Martensite, a transition substance	The next step. Some of the gamma iron is changed to beta and to alpha iron. It is harder than austenite.
Troostite, a transition substance	The third step. The quantity of gamma and beta iron constantly decreasing, that of alpha iron constantly increasing.
Osmondite	Solid solution of iron carbide in alpha iron.
Sorbite, a transition substance	A mixure of a constantly decreasing quantity of osmondite with a constantly increasing quantity of pearlite, too fine to be resolved by the microscope.
Pearlite	A conglomerate, or a mechanical mixture of free alpha iron (alpha ferrite) with the iron carbide, Fe_3C, cementite.

In a very illuminating discussion of the constitution of iron carbon alloys,[1] Albert Sauveur predicates that when steel cools slowly through the critical range and there takes place the decomposition of austenite—the solid solution of carbon and gamma iron—it first changes into a solid solution of carbon and beta iron, thence into a solid solution of carbon and alpha iron, and thence into cementite and alpha iron. In other words, Sauveur considers that, instead of the solid solution decomposing by the precipitation of its gamma ferrite, which immediately changes to beta and then to alpha ferrite, the ferrite in the solid solution is changed from gamma to beta and then to alpha, after which the precipitation occurs. By the light of recent researches this theory of Sauveur's is greatly strengthened.

Practice in Annealing, Hardening, and Tempering.

Furnaces.—There is not space here to discuss the many different types of furnaces used for heating for these purposes, but a good descriptive chapter on the subject will be found in Reference No. 149. The requisites of such a furnace are: (1) that it shall be of a uniform temperature in all parts of the heating chamber; (2) that it shall heat the pieces uniformly from all sides; (3) that its temperature shall be readily under the control of the operator. It is very desirable also that the temperature should be indicated by means of some scientific instrument instead of the unaided eye of the operator. Skillful as these operators are, it is now generally admitted that a good pyrometer will give more reliable results, and they have the further advantage of giving an autographic record of the temperature which may be kept for future reference. (4) That the metal shall not come in contact with solid fuel, because the carbon or injurious impurities in this fuel, such as sulphur and phosphorus, will be absorbed by the metal and vitiate it. The usual means of heating these furnaces is the flame from combustion of solid fuel, gas or oil, or heat converted from electric energy. Electric heat, although expensive, gives the most effective control of the temperature and also enables us to get with ease, either the highest or lowest temperatures. (5) That ready access to the pieces being heated shall be had so that they may be removed quickly and easily; (6) that the pieces shall be so supported as not to bend under their own weight

[1] *Journ. Iron and Steel Inst.*, No. 4, 1906.

at the heat to which they are subjected. (7) That means shall be provided, where possible, to prevent oxidation of the iron. This is of major importance in the case of small pieces, or of pieces which are to be treated after machining, or cold rolling, so that they shall be left with a bright surface and good corners. The means for accomplishing this object are usually to heat the pieces inside of muffles around the outside of which the combustion takes place, or else to pack them in air-tight boxes, and sometimes inside these boxes or muffles a stream of reducing gas is led to prevent oxidation, or else the metal is packed in lime or other neutral material, and sometimes a few pieces of charcoal are put inside the muffle or mixed with the lime to unite with any oxygen which finds its way into the interior. Another method of heating to prevent oxidation, which method has the further advantage of obtaining uniform temperature, heating the piece uniformly on all sides and giving an excellent control of the temperature, is to have the pieces immersed in baths of oil, lead, barium chloride, or other substances in a molten condition. These baths are then uniformly heated and transmit their temperature to the metal.

Heating for Annealing, etc.—Annealing has for its object the treble purpose of (1) relieving any strains put upon the metal during its cooling, or by mechanical treatment or otherwise; (2) to restore the grain of the metal to that minute size which gives it the best possible qualities, or (3) to soften it after hardening. We may accomplish these three objects, or any of them, in one annealing operation. The usual temperatures of annealing lie between 200° and 1000° C. (390° and 1830° F.). Temperatures from 200° to 500° C. (930° F.) are sufficient to relieve strains in the metal and to soften it because of mechanical treatment or hardening. It is only when we desire to produce a new grain size that we heat above the critical temperature, and we have already explained that for this latter purpose, it is best not to exceed the critical temperature any more than is necessary, with, however, the qualifications noted on pages 358 and 365, in the case of very bad overheating or ingotism. Where we have obtained by means of cold rolling, wire drawing, or other mechanical work in the cold, a grain size already small, it is bad practice to form a new grain size, and therefore the steel should then be heated only to that low temperature which will soften it.

Hardening Practice.—When a piece of steel is rapidly cooled, tremendous strains are developed in it as it passes through the

critical temperature. We have already studied the phenomenon of recalescence, or liberation of heat within the metal by the chemical reaction of the separation of ferrite and cementite.

The recalescing steel, which has been rapidly contracting due to the falling temperature, now tends to expand because of this liberation of heat. But, as cooling takes place from the outside inward, the outer shell of steel passes through the recalescence period first, and is already beyond that point and contracting further when the interior begins to liberate heat and tend to expand. This brings a double pressure to bear upon the steel, and the strains are so large as to frequently cause what are known as "water cracks" in the hardened steel. Sometimes the outer shell of steel actually flies to pieces under the strain, or "bursts" as it is called. Again a long cavity will be opened down the center of the piece. In the case of armor plate, for example, the appearance of cracks after the hardening of the steel is often welcomed, as it shows that the strains produced in the metal have been relieved to some extent, and a curved turret will actually be stronger under impact after cracking than before, because the latent strains are relieved. The operator must take these matters seriously into consideration, remember that the greatest strains are produced by uneven cooling which may occur through: (1) the juxta position of thick and thin sections; (2) uneven temperature of the piece which is heated up, which may best be avoided by the slow heating of large pieces; (3) uneven temperature of the bath in which the steel is quenched, or (4) careless immersion in the bath. An uneven temperature of the bath may be avoided by having small-sized baths with abundant circulation of the quenching medium therein, or else by quenching the objects in a voluminous spray of liquid, such as is practised in the hardening of armor plate, for example, the operator should move the piece around in the bath as much as is necessary to prevent vapor accumulating next to the steel and thus forming a place where the cooling is not so rapid, and the piece must be held in tongs and not allowed to drop on to the bottom of the quenching tank.

Hardened pieces occasionally warp as a result of the strains set up. This may be prevented to some extent by having the thickest parts of the piece enter the bath first, and also by annealing the specimen at a relatively low temperature before heating for hardening, in order to previously remove all strains.

It may be necessary to clamp pieces of very intricate shape in order to mechanically prevent their warping.

Quenching Baths.—The object of the quenching bath is to take the heat away from the metal at the rate of speed best suited for the hardness or other qualities desired, to be given to it. Nothing from the bath enters the steel, and it has no virtues other than to remove the heat. It may be, however, that certain baths will cool steel rapidly through the critical range and then slowly thereafter, or vice versa, and there may sometimes be virtue in this property. Saturated solutions of certain salts might deposit their dissolved substance uniformly on the surface of the steel and this incrustation may have the effect of cooling the steel more slowly at a lower temperature. Further than this characteristic, the speed of cooling will depend upon the following factors: (1) temperature of the bath; (2) heat conductivity of bath; (3) viscosity of the bath. (The importance of viscosity results from the circumstance that liquids carry heat away largely by convection); (4) specific heat of the bath, because the less the specific heat of substances, the more heat will be absorbed in a given time by the layers adjacent to the quenched body. Furthermore, the less the specific heat, the greater amount in heat will the bath absorb without rising in temperature; (5) the volatility of the liquid, because the more readily it forms vapor when heated, the more liable is there to be a cushion of vapor between the quenched body and the body of the liquid itself. Mercury, because of its low melting-point, can be refrigerated to a low point and this makes an effective hardening medium. Solutions of calcium chloride will act in the same way. On the other hand, liquid air, in spite of its very low temperature, is a poor quenching medium because of its ready volatility.

Combined Hardening and Tempering.—If steel be cooled from above the critical range by quenching in some slow heat-conducting liquid in the first instance, as cylinder oil, or melted solder at 200° C. (392° F.), the same intermediate hardening and embrittling effect will be produced upon it as if it were first hardened in water and then tempered a certain amount. Therefore the quenching in oil and similar mediums has come to be called "tempering." Another method of combining hardening and tempering after only one heating is used in the tempering of the cutting edges of chisels and similar tools: the end of the tool is first heated just above the critical range, and then the extreme

point only is quenched in water until it is black, after which it is withdrawn and rubbed bright upon a piece of sandpaper, or upon a brick. This is done merely to give a bright surface upon which to observe the play of temper colors. The heat from the shank now begins to creep down into the point, which takes the various temper colors in order, beginning with the lemon. When the desired degree of tempering is reached—say, the pigeon-wing color—the whole tool is put into water. This is merely to "put out the fire" and stop more heat coming down into the tempered-point; it has nothing to do with the tempering operation itself.

Reheating for Tempering.—A more accurate method of tempering, because it enables pyrometers to be used and because the operation can be conducted more slowly, is to allow the hardened piece to cool and then reheat it to a desired temperature at which its temper is to be drawn. By this means also we can reheat the piece in baths of lead-tin alloys, melting at low heats, which insures accurate control and that all parts of the piece are uniformly heated.

Temper Colors.—Nature has provided a ready means of determining the temperature of steel between 200° and 300° C. (390° and 570° F.) without the aid of thermometers or other instruments, and, since this is the range of temperatures in which practically all of the tempering of hardened steel takes place, this provision is a most fortunate one. It comes about through the oxidation of the metal at those different points. At 200° C. (390° F.) a thin film of oxide forms upon the steel, but is not sufficient to entirely hide the white color underneath, so that the combination produces a light lemon color. As the temperature rises the film of oxide becomes thicker and the yellow color darker until, at about 225° C. (437° F.), it has changed to faint straw.

In table XXVII are the temperatures and other phenomena relating to the treatment of steel and the temperatures for tempering various tools.

TABLE XXVII

	° F.	° C.	
Scrapers for brass	437	225	Steel engraving tools.
Light turning tools			Hammer faces.
Planers for steel	to	to	Planers for iron.
Ivory cutting tools			Paper cutters.
Wood engraving tools	455	235	Drills.
Bone cutting tools			Milling cutters.
Wire drawing plates	456	236	Boring cutters.
Leather cutting dies			Screw cutting dies.
Taps	to	to	Chasers.
Rock drills			Mill chisels and picks.
Penknives			Punches and dies.
Reamers	482	250	Shear blades.
Half-round bits			Planing and molding cutters.
Gouges			Stone cutting tools.
Plane Irons			
Twist drills	483	251	Flat drills.
Wood borers	to	to	Pressing cutters.
Cup tools			Coopers' tools.
Edging cutters	527	275	
Wood bits and augers	528	276	Cold chisels for steel.
Dental and surgical instruments			Axes and adzes.
Hack saws	to	to	Cold chisels for cast iron.
Saws for bone and ivory			Chisels for wood.
Needles, gimlets			Framing chisels.
Circular saws for metal	572	300	Screw drivers.
Saws for wood			Springs.

Case-hardening, Carbonizing, or Cementation

Steel low in carbon is soft and tough but will not withstand wear or abrasion; hard steel, on the other hand, is brittle except, of course, such a steel as manganese alloy steel, whose use is limited by price. Where a steel has to resist a combination of stresses consisting of penetration or abrasion and violent shocks, such a combination of stresses, in other words, as is brought to

bear upon armor plate, plow shares, certain gears and pinions, crank shafts, pivots in moving machinery, etc., or a combination of cutting and shocks, such as that which jail-bars and burglar-proof safes might have to resist, it is customary to have a combination of metals as explained on page 181. Or else, we may produce a high-carbon surface on a piece of soft steel by the process known as case-hardening or carbonizing. This case-hardened metal is then heat-treated by a hardening or tempering process which makes the outside very hard but leaves the interior tough and ductile. The high carbon of the outside is obtained by virtue of the so-called cementation process.

Theory of Cementation.—The principle upon which case-hardening depends is the slow absorption of carbon by iron or steel at a bright red heat as already partially explained on page 69. If a piece of soft steel be immersed in melted potassium cyanide at a temperature of 900° C. (1650° F.), the carbon contained in the cyanide will slowly penetrate the metal. It enters the steel in the form of a solid solution and the amount of carbon and the depth to which it penetrates will depend upon the following conditions in the order of their importance:

(1) The temperature of cementation.

(2) Time during which it proceeds.

(3) The kind of cement material used; for example, potassium cyanide gives a quicker penetration than pure charcoal.

(4) The kind of steel used; that is to say, manganese, chromium, tungsten, molybdenum, etc., in the steel increase the rate of cementation, while silicon, aluminum, nickel, titanium, etc., decrease it.

Temperature of Cementation.—The cementation process takes place with extreme slowness below the critical temperature of steel, and increases rapidly with the temperature above that point. It is not very advisable, however, to carry it on at a very high temperature because the long over-heating gives the core of the steel a coarse structure and makes it weak and brittle. Lake (No. 149) gives the following table for the speed of cementation with different substances at varying temperatures.

TABLE XXVIII

Temperature in degrees Fahrenheit	Materials used and rate of penetration in inches in 8 hours: Charcoal 60 per cent. + 40 per cent. of carbonate of barium	Ferro-cyanide 66 per cent. + 34 per cent. of bichromate	Potassium ferro-cyanide alone	Powdered wood charcoal alone	Temperature in degrees Centigrade
1290					700
1475	0.020	0.033	0.020	0.020	800
1650	0.088	0.069	0.079	0.048	900
1830	0.128	0.128	0.128	0.098	1000
2010	0.177	0.177	0.198	0.138	1100

A very usual temperature for cementation is 900° C. (1650° F.).

Influence of Time on Cementation.—The following two tables from Lake also show the influence of the time on the depth of penetration of the carbon for different materials.

Length of time in hours	Materials used and rate of penetration in inches at 100° C.: Carbon 60 per cent. + 40 per cent. of carbonate	Ferro-cyanide 66 per cent. + 34 per cent. of bichromate	Powered wood charcoal alone	Charcoal and carbonate of potassium	Unwashed animal black
1	0.031	0.033	0.028	0.059	0.035
2	0.039	0.037	0.053	0.078	0.059
4	0.047	0.049	0.063	0.094	0.088
6	0.078	0.074	0.072	0.011	0.106
8	0.118	0.128	0.098	0.138	0.128

Length of time in hours	Materials used and rate of penetration in inches at 900° C.: Charred leather	Ground wood charcoal	Barium carbonate and wood charcoal
2	0.045	0.028	0.055
4	0.062	0.042	0.087
8	0.080	0.062	0.111
12	0.110	0.070	0.125

Carbonizing Material.—Iron has been carbonized by means of a diamond as early as 1815 without melting the metal, which shows that pure carbon alone may accomplish the result. However, more impure forms of carbon give much more rapid carbonization, and for commercial purposes the materials used are generally charcoal from wood, with which is mixed other substances; powdered bone; charred leather or sugar, this latter being valuable because of the absence of injurious impurities; horn, animal black, lamp black, anthracite, graphite, etc. In the lamp black process it is common to deposit the soot on the surface to be carbonized by means of a smoky gas or oil flame. Gases containing carbon may also be used for cementation, of which carbon monoxide is one of the best; acetylene is also effective. We may also use liquids containing carbon, such as melted potassium cyanide, ferro-cyanide of potash (Prussian blue or ferro-prussiate of potash). It would appear that the presence of nitrogen assists in the absorption of carbon by the steel and for this reason the various animal and vegetable products mentioned above are preferred to charcoal from the purer materials. It is also common in some cases to introduce gases containing nitrogen, such as ammonia, etc., into the receptacles where the cementation is being carried on.

A very important consideration in case-hardening is that the carbonized material shall penetrate the steel at all points alike and this is assisted by the more intimate contact between the two, so that carbonizing with gas is often preferred to packing the steel in solid materials. Carbonization in liquid cyanides has the same advantage, and doubtless the nitrogen in these cyanides is an important element in their efficiency. The potassium cyanide bath is a very common means of cementation on account of the convenience of its use and readiness of control. One objection to it, however, is the very bad and poisonous fumes coming from this melted liquid.

Steel Carbonized.—We ordinarily carbonize a steel running from 0.10 to 0.22 per cent. of carbon in order to have a very tough core and also to avoid the ill effects of over-heating of the core which increases with the amount of carbon. The manganese in the steel should be low, because this not only increases the over-heating by lowering the critical temperature, but tends to make the outside case brittle. The amount of manganese should generally be under 0.35 per cent. and preferably less than 0.25

per cent. Chromium makes the outer surface harder, and refines the grain of the steel besides raising the temperature at which over-heating occurs. It increases the strength of the material, but makes it harder to machine. Many pieces for case-hardening contain from 0.50 per cent. to 1.50 per cent. of chromium. Vanadium and titanium are said to counteract to some extent the effect of chromium in making steel difficult to machine, and to increase its resistance to shock. Nickel is very valuable in case-hardened steel because it increases its strength, decreases the brittleness and the tendency of cracks to spread. From 2 to 3.50 per cent. of nickel is commonly used for high grade material which can stand the extra price. The amount of silicon is usually kept as low as possible on account of its decreasing the depth and speed of cementation, and phosphorus should be under 0.035 per cent. as this makes the metal brittle under shock.

Percentage of Carbon Added.—On the very surface of the case-hardened material, the amount of carbon will usually be nearly 1 per cent. or more, and will run as high as 2.50 per cent. in the case of a very long cementation as in the manufacture of armor plate, for example. Lake cites the case of a round bar that was carbonized to the depth of 3/16 in. and showed the following percentages of carbon in each 1/16 in. turned off the outside: 1.24, 0.85, 0.24, and 0.13 per cent.

Heat Treatment for Carbonizing.—In some cases it is customary, in order to save time and expense, to quench out the pieces as they come from the cementation furnace, but it is much better practice to cool them down to a black heat and then reheat and harden in a separate operation, because this causes a somewhat better diffusion of the carbon at the point where the case-hardening joins the core. This junction line is always a line of weakness, and when the pieces are quenched out from the quenching furnace, there is a distinct line of demarkation, which is notably shaded when the metal is reheated for hardening. Moreover, the reheating restores the grain of the steel which has been somewhat damaged by overheating during the cementation process.

XV

ALLOY STEELS

We have already described ordinary steel (which to distinguish it from the so-called alloy steels is often known as "carbon steel") as an alloy of iron and carbon. But there is another class of materials to which the specific name of "alloy steels" is applied. This comprises steels to which a controlling amount of some alloying element in addition to the carbon is added.

Definitions.—The International Committee upon the nomenclature of iron and steel defines alloy steels as "those which owe their properties chiefly to the presence of an element (or elements) other than carbon." The distinction between an element added merely to produce a slight benefit to ordinary carbon steel and the same element added to produce an alloy steel is sometimes a very delicate one. For example, manganese is added in amounts usually less than 1.50 per cent. to all Bessemer and open-hearth steels for the sake of getting rid of oxygen and neutralizing the effect of sulphur. Likewise silicon is sometimes added in amounts of 0.1 to 0.2 per cent. to get rid of blow-holes. But neither of these additions produce what is known as an alloy steel. When we make 'manganese steel' containing 10 to 20 per cent. manganese, the material has new properties quite different from the same steel without manganese and we therefore get an alloy steel. Similarly "silicon steel" containing 2 or 3 per cent. of silicon will have an entirely new set of properties due to the silicon, and will therefore become an alloy steel.

Ternary Alloys.—A ternary alloy, or three-part alloy, is an alloy composed of iron, carbon, and one other influential element. This class includes the alloy steels which are used most abundantly by man and the most important of which are nickel steel, manganese steel, chrome steel, tungsten steel, molybdenum steel, silicon steel, etc. There are several other ternary steels which have been investigated and used to a small extent, such as boron steels, cobalt steels, etc. The field of useful ternary steels has not yet been investigated except in the most meager degree and a wide scope is left for future inventors. There are many ele-

ments whose influence on steel has not yet been studied, and even among those which are commonly used, there are some of which only limited proportions have been employed.

Quarternary Steels.—Quarternary, or four part, steels consist of iron, carbon, and two other alloying elements. The commonest and most important of these are nickel-chromium steels, tungsten-manganese and tungsten-chromium steels, nickel-manganese, manganese-silicon, tungsten-molybdenum, tungsten-nickel, nickel-vanadium steels, etc., etc. The result produced by adding an alloying element to ordinary carbon steel is astonishing and incapable of being predicated, and that obtained by a combination of two alloying elements is far more so. New products result with properties entirely different, and in some cases almost the opposite, of those of its constituents, so that almost any combination at random may lead to a surprise, even when the effect of different combinations of the same components is known. Therefore the possibilities of quarternary steels seem to be very great and the field has, as yet, hardly been touched.

Manufacture of Alloy Steels.—The manufacture of alloy steels is usually very simple and calls for no special comment here. As a general thing the alloying element is added like the recarburizer. For example, in the manufacture of manganese steel the requisite amount of ferro-manganese will be added at the end of the process; in the manufacture of nickel steel we may add ferro-nickel in the same way, but it is more common here to add shotted-nickel during the process and allow it to dissolve in the steel bath and remain there until the metal is tapped; tungsten steels and tungsten-chrome steels are often made by the crucible process and the requisite amount of ferro-chrome and ferro-tungsten, or of metallic chromium and metallic tungsten, is placed on top of the charge when the crucible is filled.

The treatment of some of the alloy steels is not so simple: Nickel steel may be heated, rolled and forged without any great precaution, but these operations are performed upon manganese, tungsten, and some of the other alloy steels only after great difficulty and experience. Under the head of these different steels, I shall describe the proper method of treatment.

Nickel Steels

Nickel steels are the most important of all the alloy steels and are the most abundantly used. In the ordinary commercial

alloys the nickel ranges from 1.50 to 4.50 per cent. and usually from 2.00 to 3.75 per cent., while the carbon is usually from 0.20 to 0.50 per cent. Not counting armor-plate, which is really a quarternary steel, containing both nickel and chromium, the most important uses of nickel steel are for structural work in bridges, railroad rails, especially on curves, steel castings, ordnance, engine forgings, shafting, especially marine shafting, frame and engine parts for automobiles, wire cables, axles, especially for automobiles and railroad cars, etc., etc. We can best learn the reasons for these particular uses by discussing the distinctive properties conferred by the nickel and their usefulness.

Tensile Properties.—The chief distinction between nickel-steel and carbons-teel is the higher elastic limit of the former, and especially the fact that this higher elastic limit is obtained with only a slight decrease in ductility. About 3.50 per cent. of nickel added to carbon-steel will increase the elastic limit nearly 50 per cent., while reducing the ductility only about 15 to 20 per cent. It is this increase in elastic limit which is probably the chief reason for the increased resistance of nickel-steel to what is known as "fatigue," that is to say, its resistance to repeated stresses and alternating stresses[1] under which all steel will ultimately break down, even though the load is far less than that it can bear indefinitely if constantly applied. It is probable that the minute structure of nickel-steel is also advantageous in this same connection. About 3.50 per cent. of nickel will give steel approximately six times the life in resistance to fatigue. The records of shipping show that the great majority of accidents to vessels at sea come from the breaking of the propeller shafts which is doubtless due to alternate stresses because these long shafts are put out of alignment by each passing wave; so now practically all large vessels use hollow nickel-steel shafts. It is the higher elastic limit that is responsible also for the use of nickel-steel in bridges, ordnance, automobile parts, and wire cables, for we may obtain equal strength with less weight or greater strength with the same weight. Besides the elastic limit the ultimate tensile strength of nickel-steel is increased also by the addition of nickel. The increase is not so great in this particular, and

[1] Repeated stresses are stresses put upon a body at intervals and relieved meanwhile, while alternate stresses are stresses first in compression and then in tension, such, for instance, as the stresses in a wire that is bent backward and forward, or in a rotating shaft that is not absolutely in alignment.

consequently the elastic ratio, *i.e.*, the ratio of the elastic limit to the tensile strength, is increased still more greatly. The elastic limit of ordinary rolled carbon-steel should be at least one-half of the tensile strength, while that of 3.50 per cent. nickel-steel should be at least 60 per cent.

Crystalline Structure.—The crystalline structure of nickel-steel is more minute than ordinary carbon-steel, and this is probably one of the chief causes for the toughness of nickel-steel, and also for the fact that cracks develop in it relatively slowly; in the yielding of steel to fatigue the damage starts by the opening of a crack of microscopic proportions through the cleavage planes of the crystals, and this crack grows and spreads from crystal to crystal until it is visible to the unaided eye, after which it proceeds with still greater rapidity. As already stated, this development is much slower in nickel-steel than in carbon-steel. Furthermore if an armor plate is struck by a projectile, it does not crack so easily, and the cracks do not extend so far if the plate is made of nickel-steel. This fact and the greater strength of nickel-steel are the chief reasons for the 3.25 per cent. of nickel in all modern armor plate.

Modulus of Elasticity.—The modulus of elasticity of nickel-steel containing not more than 4 or 5 per cent. nickel is about the same as that of carbon-steel, namely, about 29,500,000 pounds per square inch. With higher contents of nickel, however, and especially with more than 20 per cent. of nickel, the modulus of elasticity is lower. This results in the steel being much more resilient or springy, and this is one of the important reasons why not more than 4 per cent. of nickel is put into structural steels, for a bridge built of steel which was resilient, even though strong, would vibrate so much with the motion of a passing load as to be unpleasant, and even unsafe on account of the repeated stresses set up. The price of nickel, of course, enters into the limitation of the amount used in structural material as well, and it is found that 3.50 per cent. can be added without great expense and with beneficial results.

Hardness.—Nickel-steel is harder than carbon-steel, though not so much so but that it can be machined without difficulty. This is taken advantage of in the use of nickel-steel railroad rails for curves and other locations where the steel soon wears out. The additional strength of the nickel-steel is also an advantage in this connection and nickel-steel rails have been tried with success

upon the famous horseshoe curve of the Pennsylvania Railroad and other places. The hardness of nickel-steel is also accompanied by a lower coefficient of friction, and those properties, together with the additional strength, are taken advantage of in the use of nickel-steel in axles for automobiles, locomotives and railroad cars. Equal strength can be obtained in an axle of smaller size which has, of course, less bearing surface, and therefore still further reduced friction.

Soundness.—Nickel-steel castings are relatively free from blow-holes and this together with the strength is a reason for the use of this material for castings. They also have a lower melting-point and run more easily in the molds.

Expansibility.—The coefficient of expansion of nickel-steel is one of its most astonishing and unusual characteristics, for in different samples it varies all the way from practically zero up to the ordinary figure for carbon-steels.

Colby[1] gives the following figures for the average coefficient of expansion for each 1° C. temperature:

Carbon-steel	0.00001036 (Guillaume)
Carbon-steel (0.25 per cent. C.)	0.00001150 (Charpy)
Soft Carbon-steel	0.00001078 (Browne)
5.00 per cent. Nickel-steel	0.00001053 (Guillaume)

Invar.—But the coefficient of expansion with the ordinary atmospheric changes of temperature becomes less and less as the percentage of nickel increases until, when we reach 36 per cent. of nickel, it is less than any metal or alloy known and amounts practically to zero. This alloy is patented and sold under the name of "Invar" and is used for scientific instruments, pendulums of clocks, steel tape-measures for accurate survey work, etc. In a paper read before the American Association for the Advancement of Science in December, 1906, it was stated that tapes made of invar used experimentally for United States Government survey work showed a very great increase in accuracy over ordinary steel tapes, and also in rapidity of use. These tapes varied an infinitesimal amount during the first few months, after which they became practically constant in length. The cause of this peculiar effect of nickel upon the dilation of steel with an increase in temperature is a result of the effect of nickel upon the critical ranges of the steel, which we shall describe later.

[1] Page 79 of No. 152.

Platinite.—As the amount of nickel increases beyond 36 per cent., there is a slight increase in the coefficient of expansion so that when we reach about 42 per cent. of nickel, the steel has the same coefficient of expansion and contraction with the atmospheric temperature as has glass. It can therefore be used for the manufacture of "armored glass," *i.e.*, a plate of glass into which a network of steel wire has been rolled and which is used for fire-proofing, etc., because even though the glass should break, it is held together by the steel network. It can also be used for the electric connections passing through the glass plugs in the base of incandescent electric lights. Platinum has been used altogether for this latter purpose, in spite of its very high cost, because it was the only metal hitherto known that had the correct coefficient of expansion and contraction, and therefore the name of "platinite" has been given to this patented nickel-steel alloy.

Corrodibility.—Nickel-steel corrodes less than carbon-steel, both in the presence of the atmosphere, fresh and salt water, the ordinary acids, the smoke of locomotives, etc. Moreover, the degree of corrodibility decreases with each increase in the amount of nickel present. For this reason 30 per cent. nickel boiler tubes have been used, especially in marine boilers. The great expense of this material is, however, an obstacle to its common adoption.

Other Properties.—Ordinary nickel-steel containing about 3.50 per cent. of nickel has several other properties which distinguish it from carbon-steel, among which we may mention its higher compressive strength and greater toughness under impact. This latter makes nickel-steel especially resistant to shocks, for it not only takes a greater blow to bend it but it will bend through more of an angle before cracking. Nickel-steel also has a greater shearing strength which makes it advantageous for rivets, because smaller rivets may be used and this means smaller holes in the structural members that are being joined, and consequently a greater area of these members left to support the strains upon them. In this connection, however, it should be remembered that nickel-steel does not weld as well as carbon-steel, and therefore greater care is required in upsetting the rivets during the processes of construction. Nickel segregates very little in iron and it also has the advantageous property of hindering the other elements from segregation, so that nickel-steel is less liable to these irregularities than carbon-steel. In steel over 0.50 per cent. car-

bon, nickel has a tendency to make the carbon come out as graphite.

Critical Changes.—Nickel has a very important effect upon the critical changes of iron and steel. This fact will readily be believed because it is known that many of the elements added to steel produce important changes in the critical points. G. B. Waterhouse,[1] while investigating the effect of 3.80 per cent. of nickel upon iron, showed that this amount of nickel did not make any appreciable difference in the mode of occurrence of the critical points on cooling, but it did reduce the temperature at which these critical points came by about 75° C. (167° F.).

As the amount of nickel in the alloys increases the temperatures at which the critical ranges occur become lower and lower until we reach 25 per cent. of nickel, when the critical ranges occur below the atmospheric temperature. That is to say, the steel does not ordinarily cool to the point at which the solid solution is decomposed and the beta and alpha allotropic modifications are assumed.

Irreversible Transformations.—The great peculiarity of the critical changes of the nickel-steel alloys with less than 25 per cent. of nickel is that they are irreversible. By this we mean that the change which takes place at one temperature on cooling is not reversed on heating at the same temperature, or anywhere near that temperature. In other words when we cool a nickel-steel containing 20 per cent. nickel the solid solution is not decomposed and the alpha allotropic modification is not assumed until we get below 100° C. (212° F.). But having cooled the steel to that point and decomposed the solution, we can now heat it nearly to 600° C. (1112° F.) before the reverse change takes place and we again form the solid solution and the gamma allotropic modification. In other words, it is possible to have a sample of nickel-steel between 100° and 600° C. which shall be in either condition we like. With 20 per cent. of nickel, nearly 1 per cent. of carbon and 1.40 per cent. of manganese, the transformation point on cooling is 188° below zero C. (306° below zero F.), while the transformation point on heating is well above the atmospheric temperature. Therefore at atmospheric temperature we may have such a piece of steel in either condition we like, and a very interesting experiment is formed by having a bar of this steel one end of which has been cooled more than 188° below zero C.,

[1] No 150.

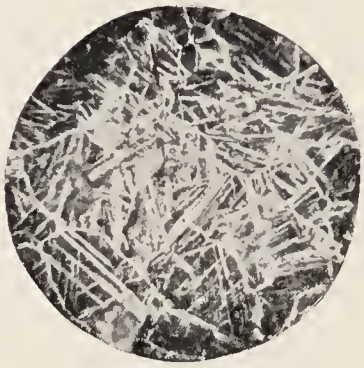


FIG. 316.—1.54 PER CENT. CARBON. ROLLED.
Magnified 225 diameters.
Etched with picric acid.

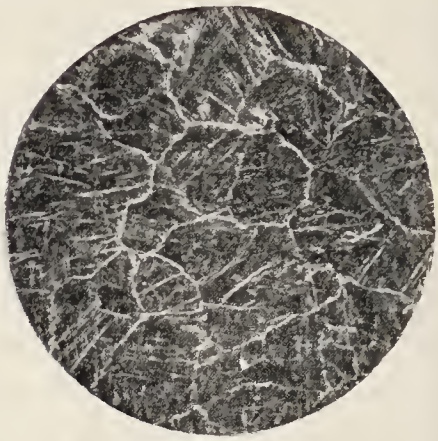


FIG. 317.—1.24 PER CENT. CARBON. ROLLED.
Magnified 225 diameters.
Etched with picric acid.

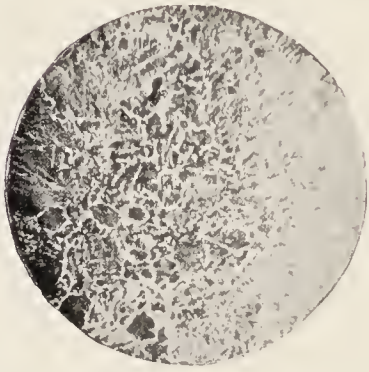


FIG. 318.—1.24 PER CENT. CARBON. SLOWLY COOLED STEEL.
Magnified 225 diameters.
Etched with picric acid.

FIG. 319.—1.24 PER CENT. CARBON COOLED EXTREMELY SLOWLY.
Magnified 265 diameters.
Etched with picric acid.

FIG. 320.—1.24 PER CENT. CARBON. COOLED EXTREMELY SLOWLY.
Magnified 265 diameters.
Etched with picric acid.

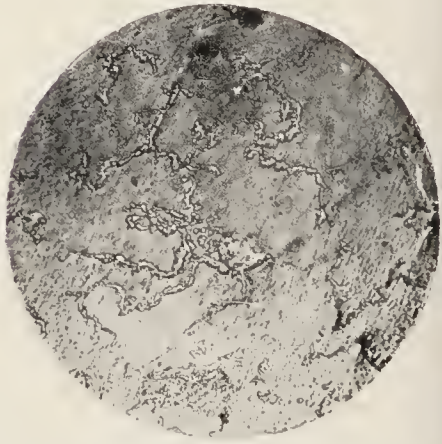


FIG. 321.—0.41 PER CENT. CARBON. COOLED EXTREMELY SLOWLY.
Magnified 265 diameters.
Etched with picric acid.

Nickel steels containing about 3.80 per cent. nickel, 0.12 per cent. silicon, 0.05 per cent. manganese, 0.014 per cent. sulphur, 0.008 per cent. phosphorus, 0.01 per cent. aluminum G. B. Waterhouse in the Author's Laboratory.)

while the other end has not. The end that has been cooled will be magnetic and the other end non-magnetic.

When we have more than 40 per cent. of nickel in our steels, the critical transformations are reversible like ordinary steels. That is to say, they occur at nearly the same temperature on heating as the reverse change does on cooling. It is an interesting fact that the steels in which the irreversibility of the transformation is most marked—that is to say, the steels from 12 to 25 per cent. of nickel—have the highest strength and elastic limit; at about 25 to 30 per cent. of nickel, where the irreversible transformation is most erratic, and beyond that point, the strength is much lower. The whole interesting question of reversible and irreversible transformation is discussed very fully in Dumas's paper No. 153.

Occurrence of Nickel.—Waterhouse tested his steel containing 3.80 per cent. of nickel and found that a part of the nickel was dissolved in the cementite which had the formula $(FeNi)_3C$. The amount of nickel in the cementite was not, however, as great as that in the ferrite. That is to say, the steel, as a whole, contained 3.80 per cent. nickel, while the cementite contained only 1.86 per cent., showing that the nickel dissolves more easily in the ferrite than it does in the cementite.

Micro-structure.—In Figs. 316 to 321 I show some photomicrographs of nickel-steels taken by Waterhouse, and in reference No. 1522 will be found L. Guillet's researches upon this subject.

Manganese Steel

We owe the discovery of manganese steel to the untiring ingenuity of Robert A. Hadfield, of Sheffield, England, and its story will be an inspiration to every inventor, for it resulted in a material whose properties are not only the opposite of what we might reasonably have expected on logical grounds, but whose combination of great hardness and great ductility was hitherto unknown and might readily have been believed to be impossible. Constant study and perseverance must have been the qualities that led to this revolutionary invention, and it has established beyond question the principle that because a given amount of any element produces a given effect upon steels, it does not follow that a different amount will give the same effect in a different degree. Indeed a different amount may give an entirely different, and perhaps an exactly contrary, effect, as is the case of the effect of manganese upon steel.

When the manganese in steel is over 1 per cent. the metal becomes hard and somewhat brittle, and these qualities increase in intensity with every increase of manganese until, when we have 4 to 5.50 per cent. the steel can be powdered under the hammer. But as the manganese is increased from this point, these properties do not increase and when we reach 7 per cent., an entirely new set of properties begin to appear. These are well marked at 10 per cent. of manganese, and reach a maximum at 12 to 15 per cent.

Composition.—Manganese steel usually contains about 12 to 13 per cent. of manganese and 1.25 to 2 per cent. of carbon.[1] With this amount of manganese the strength and ductility of the material reaches its maximum. This high carbon has been necessary hitherto, because ferro-manganese contains much carbon, which therefore unavoidably finds its way into the steel. In recent years, however, manganese metal, relatively free from carbon, has been made by the Goldschmidt thermit process and otherwise, and this enables manganese steel low in carbon to be made, which is now in process of development and is giving evidence of having new and useful properties of its own and of being more easily treated and worked.

Treatment.—After manganese steel has been cast into an ingot or casting, and slowly cooled, it is almost as brittle as glass. But it is then reheated to a temperature of more than 1000° C. (1832° F.) and rapidly cooled by plunging it into water. The temperature from which it is necessary to quench it can readily be determined, for it must be so high that when the steel is quenched little blue flames of hydrogen will appear on the surface of the water. These are due to the decomposition of water into hydrogen and oxygen by the intense heat of the steel at the moment of touching it. The steel which was very brittle before this treatment is afterward as ductile as soft carbon steel or wrought iron, while its tensile strength is about three times as great. Thus the sudden cooling, which produces brittleness in ordinary steel, produces ductility in manganese steel. The hardness of the manganese steel is about the same in the slowly cooled and in the quenched condition, and is so great that it is not commercially practicable to machine it and there is no method known of making it softer.

Manganese steel must be heated very slowly and uniformly lest it crack. It is also very difficult to forge it, and this can only be accomplished within a narrow range of temperature above a

[1] Manganese steel that is to be forged or rolled is made lower in carbon than this.

red heat and by beginning with very light taps of the hammer. After a little working it becomes so tough that it can be rolled, although somewhat gingerly.

Uses.—Manganese steel is used chiefly for the jaws and wearing parts of rock-crushing machinery and similar apparatus, for railroad frogs and crossings, for railroad rails on curves, mine car wheels, and burglar-proof safes. Its life in these classes of service is very many times that of all other kinds of steel, because it is not only extremely hard but is without brittleness. There is a famous curve on the Boston elevated railroad where carbon-steel rails were worn out in a very short time and the use of manganese steel rails has proved very advantageous and economical. The use of the steel for burglar-proof safes is also very advantageous, because there is no known method of making the steel soft enough to be penetrated by a drill. The uses of manganese steel are limited chiefly because the metal must ordinarily be formed by casting, since machining and cutting to shape is practically out of the question, and forging is difficult. For structural work the advantages of its high combination of strength and ductility are somewhat offset by its low elastic limit, which is only about 35 per cent. of its ultimate tensile strength. One peculiarity of manganese steel is that when it yields to tensile stresses it is elongated more uniformly over its whole length than carbon steel, which suffers its greatest elongation near the point of final rupture where a certain amount of "necking" takes place. It will be remembered that wrought iron stretches more uniformly over its whole length than steel; manganese steel has this property in a still more marked degree even than wrought iron.

Critical Changes.—The hardness of manganese steel is due, in part, to the hardness of manganese, but still more potently to the fact that the steel is in the austenitic condition. That is to say, the manganese has reduced the temperature at which the critical changes occur below that of the atmosphere, and therefore manganese steel consists entirely of austenite. It is, of course, non-magnetic.

Chrome Steel

Chromium has the effect of making the critical changes of steel take place at a higher temperature and much more slowly. For the latter reason chromium steels are capable of greater hardness, because rapid cooling is able more completely to prevent the

decomposition of austenite. They contain usually 1 to 2 per cent. of chromium and from 0.80 to 2 per cent. of carbon and are used in the hardened state. They are particularly adapted for making armor-piercing projectiles, on account of their hardness and also their very high elastic limit. They are also used for armor plate for the same reason, for parts of crushing machinery, and for very hard steel plate. This latter is not ordinarily used by itself, but is made into 3-ply and 5-ply plate for plows and burglar-proof safes, as described on page 181, for if the hardened chrome steel were used alone, its brittleness would cause it to be shattered.

Armor Plate.—Krupp armor plate contains about 3.25 per cent. of nickel, 1.50 per cent. of chromium and 0.25 per cent. of carbon.

Automobile Steels.—Chromium from about 0.50 to 2 per cent. is also used for automobile steels where hardness is required, as for instance in gears and other parts requiring great hardness or great strength. For the latter purpose it is more common to use a nickel-chrome steel, and this is often subjected to a double heat treatment or a simple oil tempering. This treatment has the effect of greatly increasing its strength and elastic limit, so that steels of this character will have properties similar to those shown in Table XXX. There cannot be said to be any uniform composition or method of treatment for automobile steels, and my inquiries among American manufacturers seem to indicate that there is not very much of the high-priced alloy steels used in American cars, except for the frames which, as already stated, are frequently made of 3.50 per cent. nickel-steel. The next most important use is probably for gears of chrome steel of nickel-chrome steel, first case-hardened by cementing with carbon to a depth of an eighth of an inch or so, and then heat-treated. The composition and treatment of alloy steels used in French automobiles is shown more fully in Guillet's article, No. 1514.

Self-hardening and High-speed Tool Steels

Self-hardening Steel.—Self-hardening steel is steel which is hard without being subjected to any heat treatment or other process for making it so. It is steel which cannot be made soft, or annealed, by any process known at present. It is often called "air-hardening steel" because when it cools in the air from a red

heat or above, it is not soft like ordinary steel, but is hard and capable of cutting other metals. Manganese steel is a typical self-hardening steel and so obviously is any steel which is in the austenitic condition at atmospheric temperatures—that is to say, whose critical temperature is below the atmospheric temperature. All the self-hardening steels are therefore non-magnetic.

Mushet Steel.—The name "self-hardening" steel was first applied to an alloy steel invented by Robert Mushet and which owed its self-hardening properties to the simultaneous presence of both tungsten and manganese. The analyses varied greatly, but were probably limited to between 4 and 12 per cent. of tungsten with 2 to 4 per cent. of manganese and 1.50 to 2.50 per cent. of carbon. A typical sample and one having excellent qualities contained about 9 per cent. of tungsten, 2.50 per cent. of manganese, and 1.85 per cent. of carbon. This steel is incapable of being made soft by any known process and is non-magnetic. It is one of those curious phenomena met with in the metallurgy of steel, where a combination of two elements will produce a result entirely different from anything that might be predicated: Tungsten does not lower the temperature of the critical change in steel and 2.50 per cent. of manganese has but a slight effect in that direction. Nevertheless the combination of these two reduces the critical point below the atmospheric temperature.

Mushet steel has been, for many years, a famous tool steel because of its capacity for performing a large amount of heavy cutting work. It is very hard and durable and will retain its cutting edge for a long time and under very severe service. It, or its equivalent, is used very largely at the present time for very heavy, or deep, cuts and especially for cutting extra hard metal, such as the roughing cuts on armor plate and other hard alloys. The cutting speed of which it is capable is not much, if any, greater than ordinary carbon tool steel, but the economy of its use is due to the fact that it will take such deep cuts and last so long without regrinding.

Other Self-hardening Tool Steels.—The 2.50 per cent. of manganese in Mushet steel can be replaced by 1 or 2 per cent. of chromium and again produce a self-hardening tool steel which has the advantageous properties of Mushet steel. This result is even more astonishing than the self-hardening properties of Mushet steel, because chromium has a tendency to raise the temperature at which the critical change comes, and yet the

addition of 1 or 2 per cent. of chromium to a tungsten steel, which was not previously self-hardening and whose critical temperature was about 600° C. (1112° F.), reduces the critical temperature to below the atmosphere. We may also replace the 9 per cent. of tungsten in Mushet steel with 4 to 6 per cent. of molybdenum, and it is stated that this latter change produces a self-hardening tool steel which is a little tougher than Mushet steel.

Taylor and White.—Frederick W. Taylor and Maunsel White of the Bethlehem Steel Works experimented for a long period of time with the self-hardening steels existing in 1899 and previously, for the purpose of improving them by heat treatment. The full record of these and other researches were presented by Taylor in his presidential address to the American Society of Mechanical Engineers in 1906, and form one of the most interesting records of the kind ever presented to the world. The result of these experiments was to produce a wholly new kind of steel which has fairly revolutionized the machine shop industry of the world. Taylor and White found that by applying a new method of heat treatment to the self-hardening tool steels, they gave them much greater toughness at a red heat, so that they could do their cutting work at a speed so fast that the point of the tool would become red hot with the heat of friction and the great chips of steel, which were thick and heavy on account of the depth of cut which could be made, were raised to a temperature of nearly 300° C. (572° F.). In other words, the steel tool never lost its temper nor its toughness at a red heat. The heat treatment which Taylor and White employed consisted in raising the steel almost to the melting-point and then plunging it in a bath of molten lead at a temperature between 700° and 850° C. (1300° and 1550° F.), where it was kept until it was of the same temperature as the bath, and then removed and cooled by plunging into oil. They usually followed this cooling by reheating the steel to a temperature between 370° and 670° C. (700° and 1240° F.).

The first public exhibition of the Taylor and White steel was made at the Paris Exposition in 1900 and created first incredulity and then astonishment. The amount of work performed by a tool was unheard of, as also was the speed at which the tool was made to travel through the metal it was cutting, and the length of time that elapsed before it was necessary to regrind it. It was realized that a new epoch in the tool-steel industry had been inaugurated. The fact that the method of heat treatment used

by Taylor and White was subsequently shown to be unnecessary and that therefore the manufacture of high-speed steel tools, having qualities like theirs, was begun by everybody, in no way lessens the credit due them for teaching the world how to produce a new kind of metal and effecting a tremendous decrease in the price of machine work.

High-speed Steels.—The name "high-speed steels," was not given by Taylor and White to their product, but has subsequently been adopted for all steels capable of these rapid-cutting speeds which theirs had. Soon after they had shown the world what could be done, it was found that the only heat treatment necessary to give the steel its peculiar hardness and toughness at a low red heat was to raise it to a temperature very near its melting-point and then cool it with moderate rapidity, as for example, by holding it in a blast of cold air until it was below a red heat. The essential feature seems to be that the steel shall attain a high temperature which, in many cases, is so great that melted oxide drops from it, and it is almost ready to scintillate—that is to say, it has almost crossed the line Aa in Fig. 252, page 295. After this heating it sometimes suffices to merely allow the steel to cool in air, but in this case its hardness is not as great, and cooling in a stream of air is more usual.

Composition.—It was also soon found that the composition of the self-hardening steels was not the best one for high-speed steels. Tungsten was the element which gave the steel the properties of hardness and toughness at a red heat. After the peculiar heat treatment had been learned and the presence of manganese or chromium in addition to the tungsten was shown to be unnecessary, it was found that more durable qualities could be obtained by increasing the percentage of tungsten, and steels have been put upon the market with even as high as 24 per cent. of this element. At the same time the carbon was greatly reduced and at the present usually varies from 0.40 to 0.80 per cent. in the best high-speed steels.[1]

[1] It is commonly stated in the trade that tungsten will take the place of carbon in producing hardness, but this is not true. It is far more correct to say that tungsten will assist carbon in producing hardness and therefore with high tungsten steels we may have lower carbon. This distinction may appear merely academic, but it is well worth recognition by those who expect to make a study of these steels. No amount of tungsten or any other element will make steel hard in the absence of carbon, or even when the carbon is low. The tungsten produces hardness by its effect upon the condition of the carbon—that is by helping to retain the carbon in its solid solution—and not by any effect of its own. It is for this reason that a lesser amount of carbon will produce hardness in the presence of tungsten or some similar agent.

It was also found that molybdenum could replace tungsten as far as producing high-speed qualities was concerned, and many believe that the molybdenum steels are more tough and durable than the tungsten steels. Some difficulty was met with at first in working the molybdenum steels as they proved to be seamy and liable to cracks, but this was overcome with experience. The molybdenum steels do not require so high a temperature for heating previous to cooling down in the air blast as the tungsten steels. According to the researches of Carpenter,[1] the molybdenum steels should be heated between 1000° and 1100° C. (1832° and 2012° F.), while the tungsten steels must be heated in the neighborhood of 1200° C. (2192° F.). Furthermore it only takes about one-half as much molybdenum as tungsten to produce the desired result, which means that there is more iron in the molybdenum steels than in the tungsten steels. In other respects the analysis of the molybdenum and the tungsten steels is about the same, containing usually 0.60 to 0.80 per cent. of carbon and anywhere from zero chromium up to sometimes as much as 4 per cent. Indeed chromium is sometimes recommended as high as 6 per cent. and over, because it gives hardness, but it also reduces toughness. The more durable qualities of the molybdenum steels than the tungsten steels are believed to be due to the larger amount of iron in them and the lower temperature necessary for tempering them. Vanadium is also added with beneficial results.

In some cases molybdenum and tungsten have been used together in high-speed steels. In fact there are at the present time scores of brands and analyses of high-speed steels on the market, made both in America, England, and Europe and the art of manufacturing them is constantly advancing so that no very general results can be quoted. In America the most advantageous percentages of molybdenum, 6 to 15 per cent., are patented and although at one time a great many tons of this kind of high-speed steel were manufactured and gave very good results (containing usually about 10 per cent. of molybdenum) it can now be made only by one company, so that tungsten steels are more common.

Forging.—High-speed steels can only be forged at temperatures above a bright red heat, that is to say from 1050° to 1150° C. (1922° to 2100° F.) and higher.

[1] See page 460 of No. 1517.

Annealing.—The heating and annealing of high-speed steels requires a great deal of care. They must be heated up to the annealing temperature (say about 800° C. = 1472° F.) with extreme slowness, and cooled down in lime or ashes or in the furnace. They are then soft enough to be machined easily, but not as soft as carbon steel. A shorter method of annealing is obtained by a double heating:[1] Heat slowly to 700° C. (1300° F.) and cool slowly to 400° C. (750° F.) or lower; then reheat to 700° C., hold there for 30 minutes and cool in air.

Tempering.—The reason tungsten and molybdenum produce in steel the high-speed quality of not losing a temper at a red heat is because of their effect upon the critical temperatures. Their effect seems to be to prolong the critical range of temperatures of the steel on slow cooling; that is to say, instead of the critical range coming in the neighborhood of 690° C. (1285° F.), as with the carbon steels, it begins, when the cooling is slow, at about 700° C. and spreads out all the way down to 300° or 400° C. (572° or 752° F.), or even lower. Molybdenum is more active than tungsten in causing this prolongation of the critical range. But if the steels are first heated to a very high temperature (1000° to 1100° C. for molybdenum steel and 1200° C. for tungsten = 1832° to 2012° and 2192° F. respectively) and then cooled moderately fast, this treatment suffices to prevent the critical changes altogether and preserves the steel in the austenitic condition. We know that this austenitic condition is one of hardness and toughness and its peculiarity under these circumstances is that it is not transformed into the pearlitic condition until the steels are heated to 650° C. (1202° F.) or thereabouts.

Magnetic Steels.—Strictly speaking, the steels used for permanent magnets are not high-speed steels, because, of course, they are never used for cutting work, but as their composition is so similar it seems well to introduce them here. A permanent magnet is made by putting a piece of hardened steel in a magnetic field for a few moments, as, for instance, by winding an insulated wire around it and passing an electric current through. The magnetic force which it obtains in this way will remain in it for a very long period of time. It is found that a steel containing about 4 to 5 per cent. of tungsten and 0.50 to 0.70 per cent. of carbon, if heated to a red heat (say 800° C. = 1472° F.) and quenched in water, will retain its magnetism better than ordinary

[1] See page 460 of No. 1517.

hardened carbon steel. Sometimes about 0.50 per cent. of chromium is added to the alloy also, which increases the permanency but decreases the magnetic force, the reason being no doubt that there are more gamma and less alpha molecules. (See p. 312).

Silicon Steels

The genius of Hadfield has also given us a silicon steel alloy of importance and usefulness. In 1888[1] Hadfield investigated many alloys of iron and silicon and although these showed some remarkable properties, especially in the matter of tempering and cutting qualities, they did not lead to any alloy steels that were produced in abundance. At a later period, however,[2] Hadfield developed a silicon steel which, after a double-heat treatment, showed some truly remarkable magnetic qualities. It had always been believed that pure iron had the highest magnetic force and permeability of any known substance or of any combination that could be produced, but Hadfield's new silicon steel, whose composition and treatment is shown below, had not only a greater magnetic permeability than the purest iron but also, characteristic of silicon steels, it had a high electrical resistance. Its hysteresis is, of course, low, this property always accompanying a high permeability. It is therefore a very valuable material for use in electromagnets, and in electrical generating machinery is the most efficient material known. Its high magnetic permeability gives high motor efficiency, and in addition its high electrical resistance reduces the "eddy currents" which are a source of waste.

Composition and Treatment.—Hadfield's patent covers silicon from 1 to 5 per cent., but the alloy which he recommends contains 2.75 per cent. of silicon and the smallest possible amounts of carbon, manganese, and other impurities. Before the steel is ready for use, it is subjected to a double-heat treatment by first heating it to between 900° and 1100° C. (1652° and 2012° F.) and cooling quickly, and then reheating to between 700° and 850° C. (1292° and 1562° F.) and allowing to cool very slowly. In some cases his second cooling has been extended over several days. He finds the best results by heating first to 1070° C. (1958° F.) and cooling quickly to atmospheric temperature and then heating to

[1] See No. 157.

[2] U. S. Patent 12,691. September 3, 1907.

750° C. (1382° F.) and cooling slowly, after which he sometimes again reheats to 800° C. (1472° F.) and then cools slowly.

Vanadium Steels

Vanadium steels are still in their infancy, for although the element has been used in steel metallurgy for many years, it is only recently that any important development work has been carried on. The results, however, are so very encouraging that we may expect great extension of their employment and important progress in their metallurgy. With the single exception of carbon no element has such a powerful effect upon steel as vanadium, for it is only necessary to use from 0.10 to 0.15 per cent. in order to obtain very powerful results, while 0.30 per cent. should probably not be exceeded so far as present knowledge indicates. In addition to acting as a very great strengthener of steel, especially against dynamic strains, vanadium also serves as a scavenger in getting rid of oxygen and possibly nitrogen. It is also said to decrease segregation, which we may readily believe, as most of the elements which quiet the steel have this effect. Vanadium steel also has the advantage of welding readily.

The effect of vanadium is shown very well by Tables XXX and XXXII,[1] and it will be seen how efficiently this material resists alternating stresses and the other forces producing fatigue. It is to be observed that vanadium is especially advantageous when added to nickel and to chromium steels, greatly increasing their strength, toughness, and temper. In this connection it is important to note that the nickel-vanadium steels have better quality when the carbon is low, especially if they are to be subjected to heat treatment.

It would seem that vanadium should have especial advantage in high-speed tool steels, but, strange to say, the results have not always been favorable. Nevertheless experiments in this direction continue.

Manufacture.—Pure vanadium has a very high melting-point and the element is therefore added to steel in the form of ferro-vanadium. This alloy should be added to the bath about two or three minutes after the manganese used for recarburizing, because if the vanadium is added before the manganese, it is wasted by oxidation. It therefore should be added always under reducing

[1] For which I am indebted to the American Vanadium Co.

TABLE XXX.—COMPARATIVE FIGURES—CARBON, NICKEL AND VANADIUM STEELS—PHYSICAL TESTS

A description of material	Chemical Composition					Physical Tests											
	Carbon	Manganese	Chromium	Vanadium	Nickel	Elastic limit, lbs. per sq. in.	Tensile strength, lbs. per sq. in.	Ratio per ct.	Elongation in 2″, per ct	Contraction of area, per ct.	Pendulum impacts, ft. pounds	Impact blows	Alternation of stress	Right angle bends	Torsion twists[9]	Rotary test	
																Stead	Souther
Carbon steels.[1]																	
Swedish quality—Mild[2]	12	.30				31,350	50,400	62	50	60	15		100	18	3.5	6,500	20,000
Forging quality[3]	.30	.50				38,080	69,440	54.9	32	47	8	25	120	12	2.8		
Nickel steels.—Forging quality[4]	.25–.30	.50			3.2	49,270	87,360	56.4	34	58	14	35	100	12	3.1		
						57,300	77,800	73.6	31.5	62							
Vanadium steels.—Type "A"	.25–.30	.50	1.0	.17													
Annealed 800°C						63,570	96,080	66.2	33	61					4.2	67,500	
						64,400	87,640	73.5	29	59	16.5		215				
						71,110	92,230	77.1	22	65							
						103,000	125,000	82.4	21	56	12	76	160	10			
						110,100	127,800	86.9	20	58							
						124,000	130,500	95	17	62							
Oil tempered[5]	Variation in quenching temperatures.					127,500	138,000	92	18	65							
						140,750	147,000	95	17	57							100 Million unbroken
						200,000	212,000	94	12	51							
						224,000	232,750	96	11	39							
Type "C," annealed 800° C[6]	.20	.35	.80	.15		47,030	87,360	53.8	34	53	16	69	190	18	4.56		
Type "D," spring steel,[7] normal	.45	.90	1.25	.18		101,900	162,400	62.7	13	44	4						
Annealed 800° C						82,060	114,800	71.5	30	63							
Oil tempered						221,000	235,000	93.8	10	39							
Type "E," case-hardening steel[8]	.15	.25	.30	.12		44,790	55,990	80.0	45	69	17		240		5.0		
Soft core of same after case-hardening and stripping case.						78,390	100,800	77.8	22	60	10						

[1] Fulfils the most severe crushing, bending, bulging, and expanding tests. [2] Equal to best Swedish mild steel. [3] Easily stands plate bend, D=2T. [4] Bends, etc., as forging steel. [5] .75″ round bends double cold D=2T. [6] 5/8″ sq. and 1″ round bars bend close double. [7] Twists in flat tight up; 9/16″ rod bends double. After tempering a spring of it coefficient of safe working load=40,000 with excellent cardon steel the coefficient of safe working load = 20,000. [8] Bends close double cold. [9] Nash torsion test; length 6″, diameter .75″.

TABLE XXXI.—TYPES OF VANADIUM STEEL

COMPOSITION

Type A, No. 1	Type A, No. 2	Type A, No. 3	Type B	Type C	Type D, No. 1	Type D, No. 2	Type E
Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Carbon .... .25–.30	Carbon.... .25–.30	Carbon.... .25–.30	Carbon..... .20	Carbon..... .20	Carbon.... .45–.55	Carbon ... .45–.55	Carbon.... .12–.15
Manganese . .40–.50	Manganese .40–.50	Manganese .40–.50	Manganese .30–.40	Manganese. .40	Manganese .80–1.0	Manganese .80–1.0	Manganese .20
Chromium .. .1.0	Chromium .1.0	Chromium. .1.0	Chromium. .50	Chromium.. .80	Chromium.. 1.25	Chromium. .1.25	Chromium. .30
Vanadium . .16–.18	Vanadium. .16–.18	Vanadium. .16–.18	Vanadium. .12	Vanadium.. .16	Vanadium.. 18	Vanadium. .18	Vanadium. .12

APPLICATIONS

"Light" axles. Conneeting rods. Side and main rods. Driving axles. Piston rods.	Crank shafts. Transmission parts. Crank pins.	Gears in constant. Mesh. Not unduly pressed.	Axle work. Hammer rods and where torsion is of great moment. Bolt steel.	Intermediate steel very useful for car axles, holding bolts, etc.	Solid wheels for railway use, gun barrels, crank pins.	Springs for automobile, carriage, and loeomotive work.	Case-hardening steel for all engine and machine parts.

HEAT TREATMENTS

Anneal at 800° C. for one or two hours. Cool in air or ashes according to nature of piece.	Quench from 900° C. in lard or fish oil and anneal at 550° C. for ½ to 2 hours, according to size in air.	Quench from 950° C. in lard oil and let down at 360° C. for ¼ to ½ hour preferably in lead bath, eool in air.	Normal.	Normal.	Anneal at 800° C. for one hour. Cool slowly, taking great care not to chill or to pass from 800° C. to 600° C. too quick.	Quench in oil from 900° C. and draw baek at 400° C. to 450° C. in lead bath preferred. Cool in air.	Regular case-hardening proeess.

REMARKS

All steels to be as pure as possible from sulphur and phosphorus. Sulphur may go to .035% without detriment.
With phosphorus at .02% the silieon may be .15% in "D" and .10% in "A," "B," and "C."
With phosphorus at .03% the silicon should not exceed .05% to .06% in "A" "B," and "C," or .10% in "D."

TABLE XXXII.—RESULTS OF MECHANICAL TESTS OF TYPICAL VANADIUM AND OTHER STEELS

Automobile purposes are taken, owing to requirements of same being of the most exigent nature.

Test	No. 1. Carbon "axle" steel	No. 2. Niekel "axle" steel	No. 3. Vanadium "axle steel". Type A, No. 1	No. 4. Vanadium erankshaft steel. Type A, No. 2	No. 5. Vanadium gear steel, eontinual mesh. Type A, No. 3	Nature
Yield point, lbs. per sq. in	41,330	49,270	63,570	110,100	224,000	Static
Ultimate stress, tensile strength in lbs. per sq. in	65,840	87,360	96,080	127,800	232,750	Static
Ratio	62%	56%	66%	87%	96%	Static
Elongation on 2 in	42%	34%	33%	20%	11%	Static
Contraction of area	61%	58%	61%	58%	39%	Static
Tortional twists	2.6	3.2	4.2	2.5	1.8	Static
Alternating bends	10	12	18	10	6	Intermediate
Pendulum impact, foot pounds	12.3	14	16.5	12	6	Dynamic
Alternating impact, number of stresses	960	800	2,700	1,850	800	Dynamic
Falling weight on notched bar, number of blows	25	35	69	76	.....	Dynamic
Rotary vibrations, number of revolutions	6,200	10,000	67,500	.....	.....	Dynamic

All figures obtained under eomparative conditions.

conditions. Beyond this there is no special difficulty in manufacture, as the amount of alloy used is so small and as it distributes itself readily through the metal and does not segregate.

Treatment.—Vanadium steels must be heated gradually but are forged without difficulty, although they must be worked a little tenderly at first. Like all steels, they must not be forged at too high a temperature, and like all alloy steels, they become even more brittle when forged below a black heat than carbon steel does.

Uses.—It is advantageous to use vanadium steel for practically every purpose that will stand the additional price, which is about the same as that of 3.50 per cent. nickel-steel. It is, of course, especially useful for all purposes where strength and lightness are desired, such as springs, axles, frames and other parts of railroad rolling stock and automobiles. It would also seem to have special advantages for shafts and other rotating parts. It also does very well for case-hardened gears, on account of the good combination of hardness and toughness and has been used to some extent for steel castings where resistance to vibration has been demanded.

Vanadium has also been added to cast-iron on account of its ability to remove oxygen and possibly nitrogen (if any is ever present), and because it makes the metal more fluid and tougher. It is said also to make chilled cast-iron rolls more durable and more ductile.

XVI

THE CORROSION OF IRON AND STEEL

Iron offers so little resistance to rusting or corrosion that there are almost no circumstances of service in which it can safely be placed without some means of protection from the elements. Certain parts of machinery, in situations where rusting is not very rapid, and where the metal will receive constant cleaning and oversight, are used without any protective coating, but structural work, in and outside of buildings, tin roofs,[1] wire fences, pipes, and other metallic structures, all require to be protected by some coating, such as paint, galvanizing,[2] tinning, nickel plating, oxidizing, etc. Boiler tubes and the inside of boilers, tanks, and pipes it is usually impossible to protect by paint, galvanizing, etc., and there is an annual loss of doubtless many thousands of tons of iron and steel from the decay of these classes of articles alone.

The Cause and Operation of Corrosion

The brown powder with which we are all far too familiar under the name of rust is a hydroxide of iron—ferric hydroxide, FeO_3H_3. It is formed wherever iron is exposed to the action of water and air. Neither dry air nor water free from oxygen has any effect upon it alone, but as air is always moist and ordinary water contains some oxygen in solution, the conditions for corrosion practically always prevail against the iron in service. The alternate attack of oxygen and water within a brief period is far more destructive than the attack of either one. For example, heavy rains, the splashing of water intermittently upon piers and columns, the rise and fall of the tide, etc., corrode the metal much faster than exposure all the time to either damp air or oxygenated water alone. Acids, while not essential to corrosion, greatly hasten its action, so that the presence of carbonic acid in the air, sulphurous, sulphuric, and hydrochloric acids in the

[1] Tinplate consists of a thin sheet of steel or wrought iron covered with metallic tin.
[2] I.e., coating with metallic zinc.

smoke from locomotives and other fires, all greatly increase the speed of rusting. It seems evident also that at least some weak electrolysis is essential for any corrosion to occur. I shall show later that this electrolytic action will always take place where iron and water are in contact with each other, but it is very small in amount under these conditions. Where a greater electric force exists, as for example where pipe lines run close to trolley tracks and receive a leak of electricity so as to carry a part of the current, the electrolytic action is increased and corrosion much hastened. As the use of electricity to-day is far more general than ever before and the amount of coal burned and consequently the amount of corrosive gases in our atmosphere is much larger, it follows that the question of corrosion is of constantly increasing importance. Affairs have indeed reached such a state that the subject is now occupying a great deal of attention from metallurgists and engineers in the hope of getting better means of protection. Pipe lines embedded in the earth, which are alternately wet and dry, supports in tunnels, subways, and other damp places, wire fences and tin roofs are all suffering severely from decay.

Theories of Corrosion.—In an able research,[1] Allerton S. Cushman has studied the current theories that have been advanced to account for the corrosion of steel. He shows that the theory that carbonic acid, or some other acid, is necessary is wrong, and that corrosion will take place even in weak alkaline solutions. He also shows that hydrogen peroxide is not the agency producing the rust. By means of a series of extremely careful and accurate experiments he demonstrated the probability, if not, indeed, the certainty, that the two factors without which the corrosion of iron is impossible are electrolysis and the presence of hydrogen in the electrolyzed or "ionic" condition. In brief, it is the ions of hydrogen which first cause the metal to pass in solution:

$$Fe + (4H + 2O)^{2} = FeO_2H_2 + H_2$$

Ions of hydrogen are electropositive to iron, and when the reaction takes place, they transfer their electric charge to the metal. This is, of course, an electrolytic action and the hydrogen which takes part in it is converted from the electrolyzed (or ionic) condition to the atomic (or gaseous) condition. Therefore it is

[1] See No. 160.

[2] $4H + 2O = 2H_2O$ in the electrolyzed condition.

evident that the action must take place in the presence of oxygen, or some other oxidizing agent that will complete the electrolysis, else the formation of ferrous hydroxide will soon cease. This explains why the presence of oxygen so greatly increases the corrosion of iron, although it is not the oxygen itself which, after all, is the cause of the primary attack.

Unfortunately traces of ionic hydrogen are always present even in the purest water, and larger amounts in ordinary water. Substances which increased the hydrogen ions, such as oxides, promote the rusting, and the same may be said of anything which increases the electrolytic action, while substances which restrain the formation of hydrogen ions will decrease corrosion. Indeed, dipping a piece of bright iron into a solution of potassium bichromate and then wiping if off will put it into an apparently oxidized condition in which it will resist corrosion for days or even weeks. Cushman, therefore, suggests dissolving a small amount of chromic acid or potassium bichromate in boiler waters in order to restrain corrosion of the metal.

Rust.—Ferrous hydroxide, FeO_2H_2, is soluble in water and its formation and solution is the first step in the production of rust. Because of its solubility, however, it does not ordinarily make its presence known until a further reaction occurs:

$$2\,FeO_2H_2 + H_2O + O = 2\,FeO_3H_3.$$

The rust, FeO_3H_3, so formed precipitates from solution.

Segregation.—Evidently anything that increases the electrolytic activity will increase the attack by hydrogen and therefore the formation of rust. Unfortunately even the purest piece of iron will show differences of electric potential at different parts and therefore produce an electrolytic effect. When the metal is impure or is badly segregated, these differences in potential will be quite large, and when several pieces of steel are joined together, as in a bridge or other structure, the difference in potential between the different parts may be great. It is probable that each of the different microscopic constitutents of iron and steel has a different electric potential and therefore either assists or retards the progress of rusting. Also scale, the slag in wrought iron, etc.

Self-protection from Corrosion.—It is generally believed that certain constituents in iron and steel assist in protecting underlying layers of the metal from attack. For example, the graphite which forms such a large proportion (say 10 per cent. or more)

of the volume of cast iron, slag which forms nearly 4 per cent. of the volume of wrought iron, and cementite in steel, all corrode less rapidly than the pure metal, and it is probable that they are beneficial in protecting it. It must not be forgotten, however, that they likewise cause a difference in potential and to that extent probably tend to hasten corrosion. Their net effect can be

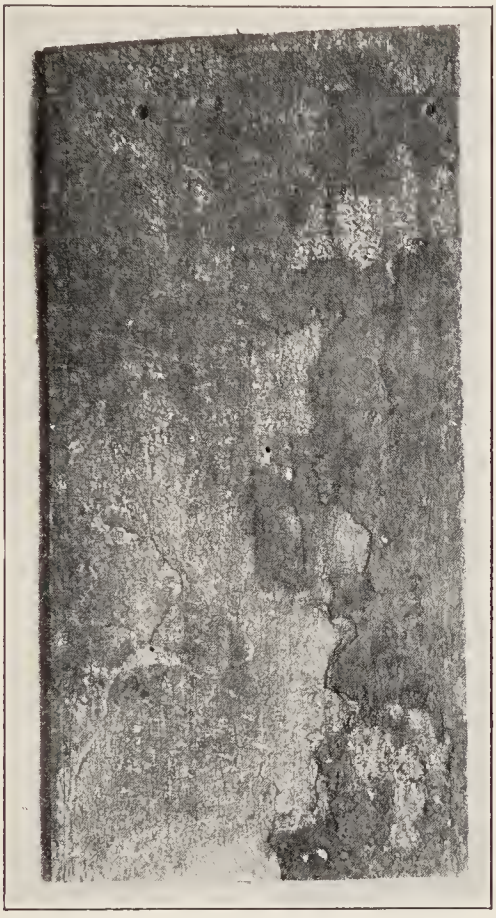


FIG. 325.—CORRODED STEEL PLATE.

learned only by experiment. Scale or foreign substances on the surface of the metal would also produce large differences in potential.

Relative Corrosion of Iron and Steel.—It is generally believed that cast iron corrodes less rapidly than either wrought iron or steel and, for this reason, cast-iron pipe is greatly preferred for city water mains and like uses where great strength is not required. The belief is a reasonable one, since it might well be expected that the presence of graphite would be a protection, but

it is only right to remark that the theory rests upon no experimental evidence and that there are other circumstances connected with cast-iron pipe which may not have given rise to the belief but which are not inherent in the material itself. These conditions are (1) the common practice of dipping cast-iron pipe in asphaltum, paint, or some similar protecting material, before it is sold and thus putting it in a condition to be in service for a long time before the metal itself is subjected to the corrosive influences. (2) When the iron is cast in the sand there seems to take place some union between the metal and the inside surface of the mold, whereby a very resisting silicious coating or "skin" is formed on the casting. Some believe that after this skin is worn away, cast iron corrodes as rapidly as wrought iron or steel. (3) Cast-iron pipe is thicker than the same diameter of wrought iron and steel pipe, because of the difficulty of making castings with thin sections of metal; therefore such pipe would remain in service much longer than steel or wrought iron, even though the rate of corrosion were the same. I have cited the above facts not to argue against the belief in the slow corrosion of cast iron, but merely to explain the situation as it exists, for we have as yet no scientific data upon which to form an opinion either way.

Wrought Iron vs. Steel.—There is also a very prevalent and widespread conviction that steel corrodes much more rapidly than wrought iron. This opinion too rests upon no very exact experimental evidence, although there are not incidents lacking which make in favor of it, while others make in the opposite direction, but it seems to be based principally upon the fact that corrosion is very much more rapid to-day, when steel is the world's great metal, than it was some years ago when wrought iron was chiefly used! But I have already shown that conditions to-day are more conducive to rapid corrosion than they were at any previous time.[1]

Opposed to this popular belief is the result of a great many scientific tests which have shown, in almost every case, that the

[1] Indeed I hardly think that this argument ought to have anything like the weight that is popularly given to it. It is not at all uncommon to hear the statement that wrought iron made 20 years ago is still in service in places and conditions alongside of steel which has been replaced several times. But I am informed by a testing engineer of much experience and reputation that he has a steel fence upon his property which has been in service many years and has outlasted several other steel fences under similar conditions, but formed of steel made recently. From this he argues that the steel made to-day is more subject to corrosion than the steel made many years ago. If this is so, we are permitted to ask: Is the wrought iron made to-day more subject to corrosion than the wrought iron made several years ago?

difference in the speed of corrosion between wrought iron and steel is very small, although favorable to wrought iron in the case of sea water and alkaline water and to steel in the case of acids and acidulated water. As has been pointed out, however, these scientific tests are not altogether reliable as a basis for commercial comparison, because they have not usually been carried to the point where either one material or the other becomes unfit for service, but merely allow corrosion to proceed for several

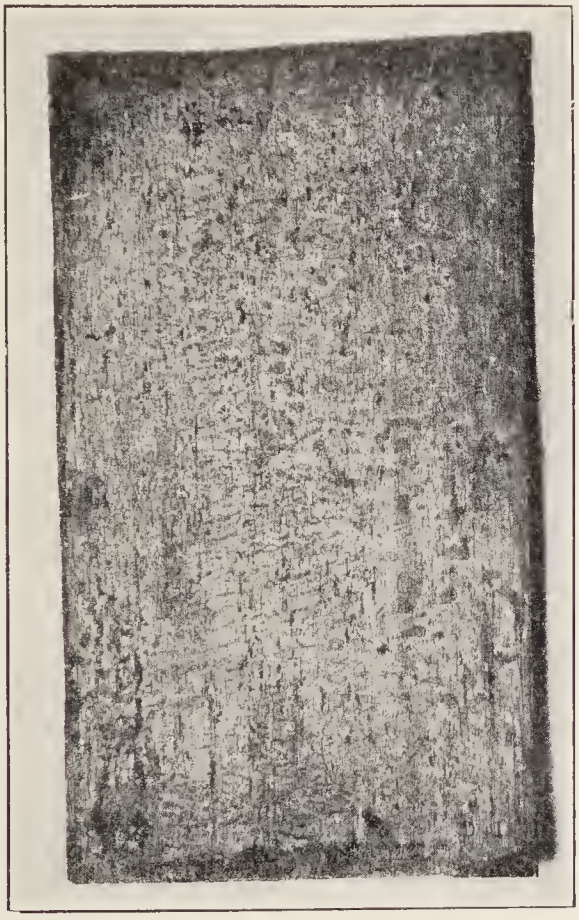


FIG. 326.—CORRODED WROUGHT-IRON PLATE.

months and then show the relative loss in weight. Neither have these experiments taken into account sufficiently the localized, i.e., "pitting," corrosion to which badly made material is especially subject. It is immaterial whether or not the metal has lost but little weight, provided it has pitted in any one spot sufficiently to fail, or to have become dangerously thin. This

pitting is believed to be due chiefly to blowholes and possibly to segregation resulting in a local increase in electric potential.

Manganese and Corrosion.—It has been suggested that the presence of manganese in steel causes an increase in the rate of corrosion, but this assertion is based upon no reliable evidence so far as I am aware. It was brought forward to explain the supposed rapid corrosion of steel as compared with wrought iron, but if it is a true influence in this direction, then steel should corrode in acids faster than wrought iron, which it apparently does not if the steel has been made with due care and is free from blowholes and much segregation.

Badly Made Material.—There can be no doubt that badly made steel is much more liable to corrosion and to pitting than well-made steel, and it may be from this cause that the bad name which steel is popularly given comes. There can also be no doubt that badly made wrought iron is extraordinarily subject to rusting, and of this kind of material we are to-day getting a good deal. As noted on page 47, probably more than half of the wrought iron produced in America is made by "busheling" scrap into a pile, rolling it down and marketing it as wrought iron. This material is of good quality so long as the scrap from which it is made is good, but when the scrap is collected form almost any source, and especially when it contains steel, as it sometimes does, we should expect great differences in potential and therefore rapid corrosion.

Coating.—Wrought iron has one advantage over steel in the case of articles which are to be coated, because its rough surface gives a better opportunity for the paint to adhere than the comparatively smooth and even surface of steel.

Summary.—Badly made steel and badly made wrought iron corrode faster than any other material; next in order come well-made steel and well-made wrought iron, between which two classes the difference is probably very slight, and has not been determined by any sufficiently lengthy or convincing series of tests; the next in order is probably cast iron, although as yet we cannot be quite certain that this corrodes more slowly than wrought iron and steel, except in so far as it is protected by its natural or artificial coating or both. Steel and wrought iron are both liable to pitting, which may greatly shorten their life in service even though the average rate at which they corrode is slow. Several causes may produce this pitting, such as blow-

holes, segregation, bad welding in places, particles of oxide, scale or dirt, etc. When pits or holes are found with a smooth, hollow surface, it is altogether probable that they are due to blowholes and sometimes these pits may be an inch or more in diameter and extend an eighth of an inch into the plate, even before the remainder of the surface has become severely attacked. Numerous efforts are being made at the present time to improve the quality of steel and to turn out a more uniform grade of product. It is quite certain that painting is not as good to-day as it was in years past and that the quality of paint used is also worse, on the average, as shown by the fact that paint does not last as well on wooden structures. The better adherence of paint gives an advantage to wrought iron, which, however, only applies where work is so placed as to be capable of being painted.

Preservative Coatings for Iron and Steel

The oxidized surface which all steel retains after hot working is in itself a certain protection against corrosion, but this is only limited in effect, because the oxide is more or less porous and so allows the corrosive agencies to penetrate it and attack the surface underneath. Moreover, the scale does not adhere firmly in some places, and as its coefficient of expansion and contraction is different from that of the metal, it is liable to loosen and fall off in places and so expose the iron or steel.

Preparation of Surfaces for Coating.—It is not advisable to coat wrought iron or steel until its surface has been carefully prepared, for any rust or other product of corrosion, scale, grease, dirt, or moisture underneath the coat will either start corrosion or else, by becoming loosened, will cause the paint or galvanizing to fall off and so expose the metal underneath. The opposite is the case with cast iron, because when this metal is poured liquid into the mold a skin is formed, consisting of a chemical union of silica and oxide of iron, very firmly united to the metal and capable of being relied upon to adhere beneath the paint or other coating and serve as additional protection from corrosion. So much mill scale as adheres to wrought iron and steel with great force is permitted by some engineers to remain underneath the protective coating, but others insist upon the removal even of this upon the ground that it may become loosened later by expansion and contraction, and then spall off.

Priming Coat.—A difference of opinion exists as to the advisability of having wrought-iron and steel surfaces prepared at the mill and there given a priming coat, or else having the priming coat applied under the direction of the engineer of construction, or else of omitting the priming coat altogether and not painting the structure at all (except such parts of it as will be inaccessible after erection) until the metal has been exposed so long that the weather has loosened all the scale. This will occupy perhaps six months to a year, depending upon the corrosive conditions. During that time no great damage can be done by corrosion although the structure will, of course, look very shabby. After that period the scale is removed with sand blast, wire brushes, pneumatic hammers, or chisels, and after the surface is perfectly clean and dry, it is given a priming coat and at least two other good coats of paint, each one being allowed to dry thoroughly before the next is spread. For indoor work one coat of paint upon the priming coat is often considered sufficient.

Shop vs. Field Painting.—The advantage of painting the steel at the shop is that it can be done inside of some building and there is therefore less liability of hygroscopic moisture under the coating. If the shop coat is put on with care and skill it unquestionably has certain advantages, but it is too true that the shop painting and the preparation of surfaces at the shop is often carelessly done, for the manufacturer has not the interest in preserving the metal from decay that the consumer feels. Furthermore it undoubtedly saves expense to allow the structure to stand from six months to a year, provided that it is then very thoroughly cleaned and well painted when absolutely dry. If otherwise the whole work may have to be done over again at the end of a short interval.[1]

Pickling.—To remove scale it is customary in many cases to pickle the steel or wrought iron, i.e., to immerse it in dilute sulphuric acid (say 10 per cent.) preferably heated to boiling so as to act more quickly. After a few minutes the scale is removed, when the metal is washed once in boiling water, once in cold water, and finally in lime water to neutralize the last traces of the acid. It should remain in the lime water until it is ready for the application of the coating, when it should first be washed

[1] In which event it is customary for all interested parties to blame the paint, except the paint-maker who is in the minority.

free of lime, and then heated slightly above 100° C. (212° F.) to drive off all the moisture. Pickling is therefore applicable only when the metal is to be coated at the shop, either with the priming coat of paint or with zinc, tin, etc.

Comparison of Methods.—Pickling costs less than the other methods of removing scale and accomplishes the work very thoroughly. Sand blast is the next cheapest method. This latter does not get off all the scale unless it is very thorough, while if it is too thorough, it leaves the surface in a smooth condition so that the paint does not stick so well. On the other hand, pickling must be done with great care or it may leave hydrogen upon the surface of the metal which will greatly hasten corrosion so that pickled surfaces sometimes corrode more rapidly than those which have been cleaned in any other way. Cleaning with wire brushes is more expensive than sand blasting, but if performed with great care is more effective and leaves the surface in a rougher condition which assists the adherence of the paint.

Kinds of Paint Used.—There is a great difference of opinion as to the best paint for preserving iron and steel, but some few things seem sertain: (1) That no one kind of paint is suitable protection against all corrosive influences. For example, the best paint to withstand the action of the open air may fail when exposed to the elements in a damp tunnel, or when used on the parts of pries under sea water, while a good protection against this latter influence might be inefficient when exposed to the oxidizing gases in locomotive smoke, etc.; (2) that whatever paint is used must be sufficiently elastic to expand and contract with the changes in temperature of the metal without cracking; and (3) that it must contain nothing which will attack the metal and so commence corrosion. In this last connection we must especially avoid all oxidizing influences. The reader will find in the *Annual Proceedings of the American Society for Testing Materials* a very full interchange of opinions between experts in paint manufacture and engineering which will doubtless help him to form an opinion as to the best paint to use in each case.

There are two parts to every paint: (1) The vehicle which carries the pigment and undergoes a change to the solid state when the paint dries, and (2) the pigment or originally solid part of the preservative coating. These two must form a firm impervious coating upon the surface of the metal, but must not be so solid as to be inelastic or brittle.

Linseed Oil.—Linseed oil is a very good and common vehicle.[1] It is what is known as a "drying oil." That is to say, an oil which when exposed to the atmosphere will change from a liquid to an elastic or leathery consistency. This action takes place not by evaporation but by a process of oxidation, whereby the oil absorbs oxygen to the extent of form 10 to 18 per cent. of its weight and expands in volume, so that a coat of linseed oil spread upon glass will wrinkle up upon drying. It is because linseed is the best of all the drying oils that it is so much preferred as a paint vehicle, but when allowed to dry in the raw state it requires too long a time and the drying is therefore hastened by boiling it and adding some oxidizing agent, known as a "drier," of which the best, as far as iron and steel preservation is concerned, are the salts of lead or manganese, used without rosin. It will readily be understood how dangerous it is to indiscriminately use driers (i.e., oxidizing agents) in steel paints, because so many of them will oxidize the steel and so cause the very corrosion which it is the object of the paint to prepent.

Purity of Linseed.—This brings us to the question of the purity of linseed oil, for the usual adulterants are all harmful to steel work and cause in the end more painting and more of the expensive cleaning of structures to receive the coating, out of all proportion to their lesser first cost. Freedom from adulterants probably cannot be obtained expect by constant watchfulness and frequent chemical analysis on the part of the consumer. Some impurity arises from the presence of a few per cent. of foreign seeds with the linseed, which is not always avoidable, but the greater harm comes from the fact that the oil is obtained from the linseed by pressing it while hot, in which way a larger amount of product is extracted than if cold pressure is applied, because some of the solid part of the seeds are thereby extracted together with the oil. Cold pressed linseed oil has a golden yellow color and remains clear in cold weather as distinguished from the yellowish-brown color of the hot pressed oil which also has a more acrid taste, is not so fluid, and contains more solid fats, solid organic matter, and fatty acids, all of which are harmful either because they attack the metal or else because they make a pervious paint.

Pigments.—The pigment is not as important as the vehicle and many different ones can be chosen, provided they are chem-

[1] See page 336 of No. 163; page 41 of No. 164.

of zinc and of iron, it is sufficiently high to produce an alloy between the two, forming, it is said, a very resisting coating which is more thoroughly attached to the surface of the metal and therefore much more durable against cracking off.

Comparison of Galvanizing Methods.—Cold galvanizing deposits a thinner coating of zinc which, if improperly performed, is liable to be porous or spongy, but it gives a better connection between iron and zinc and therefore a more durable coating. Hot galvanizing necessitates the use of a flux on the bath of melted zinc in order that the zinc may not be oxidized by air, and these fluxes probably have the effect of sometimes beginning the corrosion of the iron underneath the layer of zinc. The process of dry galvanizing is too new yet for any comparison to be drawn.

Tinning.—A large amount of metal is coated with tin in order to give protection against organic acids, such as those present in cooked foods, and also in order to give a more effective resistance to the elements. Thus cooking utensils, roofing sheets, tin cans for preserves, and many such articles are coated with tin in preference to zinc, either because zinc would not withstand so long the corrosive influence, or else would not resist it at all. In the tinning operations the metal sheets are usually drawn through a bath of liquid tin by four to six pairs of rolls which are immersed in it. Each pair of rolls presses the tin which has solidified on the surface of the iron firmly upon the metal and the result is a smooth, bright, adhering coat which protects the metal very successfully. Tin plating is more expensive than galvanizing, chiefly on account of the additional cost of the tin.

Terne Plate.—Sometimes sheet metal is coated with a mixture of two-thirds lead and one-third tin and then goes under the name of terne plate, which is used very largely for roofing and out door purposes. It is applied by the same method as tinning but is less expensive.

Nickel Plating.—Articles requiring a very high polish and which are to be subjected to handling, etc., are often plated with nickel. This is an electrolytic process, similar to the general operation described under the electrolytic galvanizing. Nickel plating is more expensive than galvanizing or tinning, but gives a more highly resisting surface.

Oxidized Coating.—There are one or two processes by which a black oxidized surface can be given to iron and steel which will re-

sist rust for years and form what are known as "black iron" objects. It is used chiefly for fancy iron work in house decorations, etc.

Enameling.—A number of articles, such as bath tubs, washbowls, cooking utensils, are made of cast iron or steel and then coated with a white or variously colored film known as enamel. Enameling processes are more or less secret, but usually consist in powdering the enamel upon the surface of the metallic article which has been heated to a red heat. At this temperature the mixtures forming the enamel melt and spread themselves uniformly over the surface where they chill and harden. Enamel must be insoluble in water and in chemicals with which they are liable to come in contact, and must also be sufficiently elastic to expand and contract with the metal without breaking off.

XVII

THE ELECTRO-METALLURGY OF IRON AND STEEL

In the electric smelting and refining of iron and steel, six modifications in practice are produced:

1. Practically any desired temperature in reason may be obtained. A corrolary to this is, that a "super-refining" of steel is possible, whereby we may reduce sulphur to a lower content than may be ordinarily achieved in the older processes; likewise, dissolved gases, occluded slags, etc., may be eliminated from the liquid metal by means of heat, instead of by means of manganese, silicon, titanium, etc. In brief, the strength of Bessemer or basic open-hearth steel may be increased some 10,000 lbs. per sq. in. by a "super-refining" in the electric furnace.

2. The impurities introduced with the usual fuels are avoided.

3. The temperature is regulated with much greater accuracy.

4. The cost of the process is greater than Bessemer or open hearth.

5. Very little, if any, fuel is required, and that only for reduction, since heat is produced by electrical means (with certain qualifications hereafter mentioned).

6. Oxygen is not necessarily introduced into the furnace in which the operation is carried on.

For many years the first three modifications have been taken advantage of in the production of ferro-alloys—e.g., ferro-tungsten, ferro-chrome, ferro-molybdenum, etc.—that is, alloys of pig iron and some other metal which is used for recarburizing in the manufacture of alloy steels. The high temperature necessary for the production of these alloys gives electric smelting especial advantages while the high price at which they can be sold enables their manufacturers to stand the additional expense with profit. But in the year 1900 a number of important electro-metallurgists in Europe and America began to use electric processes also for the production of pig iron and steel on a commercial scale, and from this time the industry dates. Because the electric processes have apparently secured for themselves a permanent place in the metallurgy of iron and steel; because of the great interest which

they have evoked on account of the new and valuable metallurgical principles involved; because the production now amounts to figures well worthy of consideration, and finally, because the electric steel seems to rival, or even surpass, crucible steel in quality, and to ultimately replace it in large part—we could well devote more space to them than the limits of this volume permit. Entire books could, and have been, profitably devoted to the subject, to which readers must be referred for a more extended discussion.

Iron and steel electro-metallurgical processes naturally divide themselves into four classes:

(1) Ore smelting for the production of pig iron;

(2) Refining of pig iron to produce steel;

(3) Super-refining of steels made by other processes, and

(4) Electrolytic refining of steel or wrought iron to produce almost chemically pure iron.

The first three classes are electro-thermic; that is to say, they use electricity for conversion into heat; the fourth class is electrolytic, that is to say, the electric current serves to produce chemical changes.

Electro-thermic Iron Ore Smelting

Electric ore smelting to produce ordinary pig iron (not including ferro-alloys) has been successful where coke and pig iron are both costly, but ore is readily obtainable. The explanation for this is that the consumption of coke in the ordinary iron blast furnace is seldom less than 2000 lbs. per ton of pig iron produced, and may be much more than that; whereas electric smelting may reduce this consumption to well under a third of that figure. It may also replace coke by charcoal for reduction, in localities where the latter fuel is cheaper. J. W. Richards[1] has shown that electric furnace smelting cannot use more than one-third as much carbon as ordinary blast furnace smelting, nor less than two-ninths. The ore-smelting furnace about which the largest amount of data is available, is the so-called "Domnarfvet" furnace in Sweden, and we may use this as an example of this process:

Domnarfvet Furnace.—The construction of this furnace is shown in Fig. 327, and its operation briefly indicated: Alter-

[1] Transactions of the American Electro-Chemical Society, 1909, xv, page 56.

nating current of 3 phase and 25 cycles, and capable of adjustment by small intervals from 20 to 80 volts, is introduced through three carbon electrodes between which the descending charge is made to pass. The total power avail-

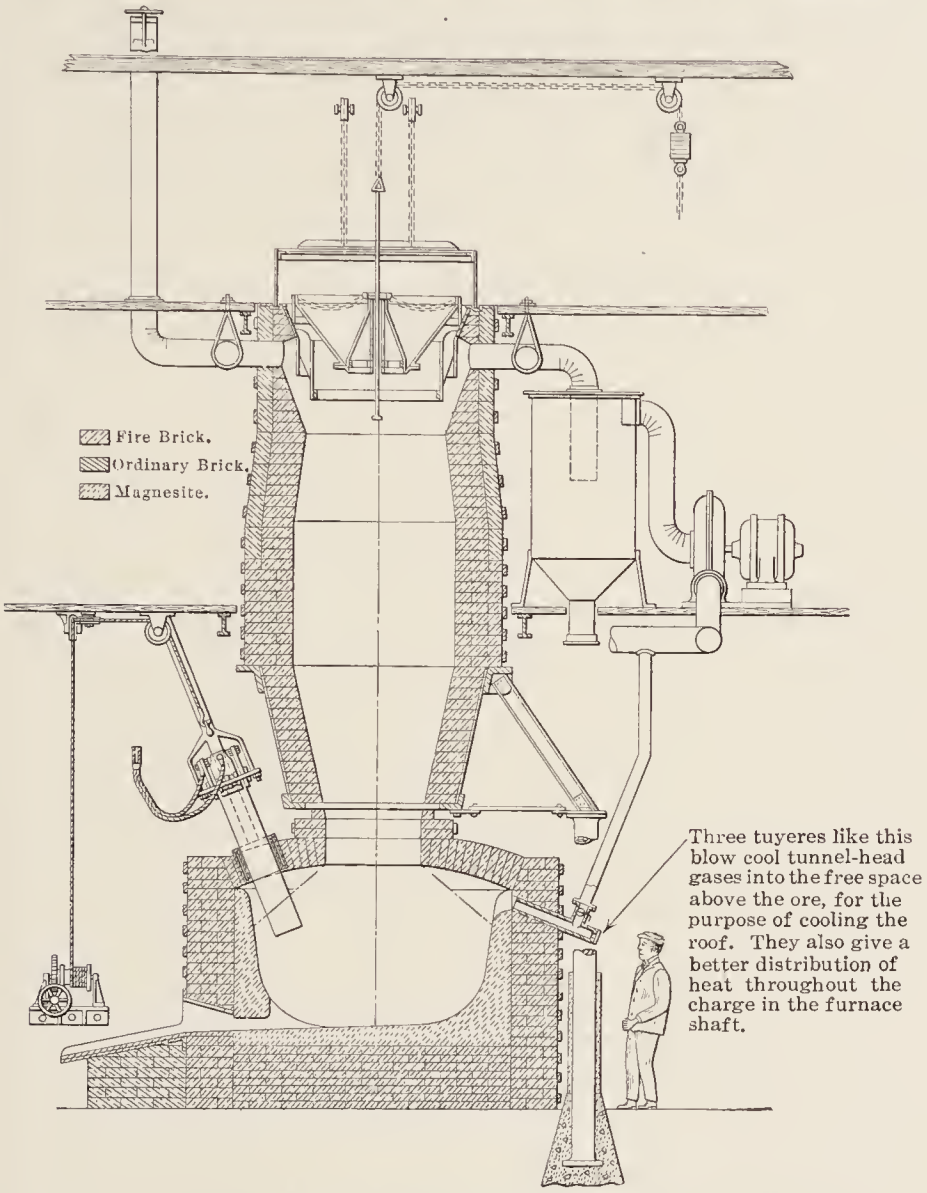

Fire Brick.
Ordinary Brick.
Magnesite.
Three tuyeres like this blow cool tunnel-head gases into the free space above the ore, for the purpose of cooling the roof. They also give a better distribution of heat throughout the charge in the furnace shaft.

FIG. 327.—SECTIONAL ELEVATION OF ELECTRIC SHAFT FURNACE, AT DOMNARFVET, SWEDEN.

able is 800 hp. The fuel in the charge conducts the current, and the resistance of the charge transforms the electric into heat energy. By means of the heat so produced, the carbon reduces the iron from the ore, and is itself oxidized. The

resulting gases pass upward, giving their heat to the charge in the furnace shaft and also performing some preliminary reduction. The tunnel-head gases are returned to the crucible for cooling purposes, and, by varying the speed of their circulation, the relative amount of CO_2 to CO may be made approximately equal, whereby the temperature of gases at the top will be kept at about 200 to 300° C. (392 to 572° F.). There is much ore reduced in the upper part of the furnace, just as in the blast furnace, but the efficiency of reduction is greater in this electric furnace, as is indicated by the larger relative proportion of CO_2 to CO.

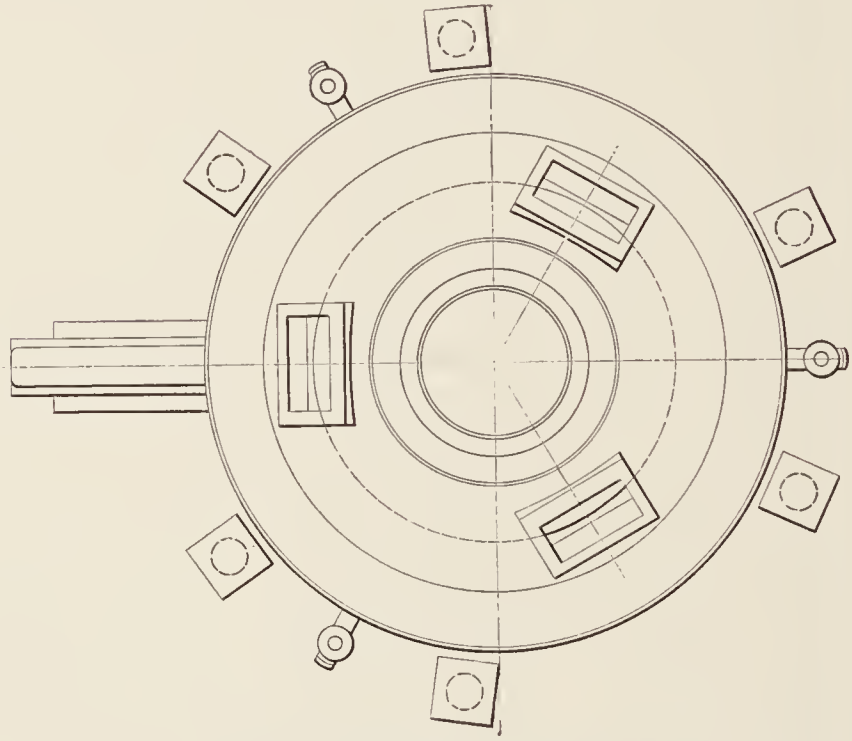


FIG. 328.—PLAN VIEW OF DOMNARFVET FURNACE WITH SHAFT AND ELECTRODES REMOVED.

Designed by Grönwall, Lindblad and Stalhane. (Sometimes also known as the furnace of Aktiebolaget Electrometall.)

The crucible does not support the shaft, but the latter rests on six columns, as shown. Shaft and crucible are filled with ore, except where the angle of rest of the charge leaves a space under the roof of the crucible, as indicated by the dotted lines. This free space is essential, and avoids the contact of electrodes with the charge adjacent to the furnace brickwork. By this means, de-

struction of the lining, which is rapid when the electrode contact with the ore is near the wall, is greatly reduced.

The melting zone is located between the three electrodes, and the control of temperature (by means of varying the electric tension) is excellent, as shown by the ability to regulate the silicon in the pig iron at will, and the ready removal of sulphur by means of a high heat and basic slag. From ores containing 0.5 per cent. of sulphur, iron was made with only 0.005 per cent. of that element. An important factor in this removal is probably the calcium carbide formed by the electric current. Phosphorus is not under control, but substantially all that present in ores and fuel, goes into the metal. With pure ores and charcoal for reduction, low-phosphorous pig iron can be made, however.

The voltage and amperes under certain conditions are shown in the following table:

Charge	Volts across electrodes	Current per electrode in amperes
Coke in excess	34	9,600
Coke not in excess	36	8,800
Charcoal in deficiency	60	6,300
Charcoal right	54	7,600
Charcoal in excess	48	7,600
Coke and charcoal in excess	35	9,200
Coke and charcoal right	48	7,600

The electric efficiency runs up to 58 per cent., and the average consumption of electric energy in seven trial runs was 0.492 hp. year per metric ton of pig iron produced; the best figure obtained was 0.383 hp. year. If metal is allowed to accumulate in the hearth, the voltage drops; the usual practice is to cast every 6 hours. The capacity of the furnace is described as about 6 tons per day. With 100 kilos of ore the furnace will use about 4 kilos of calcined lime, together with 21 to 28 kilos of charcoal; or else 22 to 24 kilos of coke in place of the charcoal. The total carbon consumption per metric ton of pig iron produced, under favorable conditions, will be in the neighborhood of 560 lbs., and may be calculated from the following formulæ:

When smelting hematite: $$\frac{321.43\ (100-k)\ +\ 10\ k}{100+m}$$

When smelting magnetite: $$\frac{285.7\ (100-k)\ +\ 10\ k}{100+m}$$

where k is the percentage of carbon in the iron, and m is the volumetric percentage of CO_2 in the tunnel-head gas. The consumption of electrodes—always a costly item in electric furnaces using carbon for this purpose—varies from 24.5 to 42.7 lbs. per metric ton of iron produced. If means could be devised of using the "stub" of the electrodes, the consumption might be reduced by 40 per cent. On the basis of the practice described above, the cost for smelting a metric ton (2204 lbs.) of pig iron will be as follows, omitting the cost for ore, limestone and patent royalties, which can be figured for each individual case:

Charcoal at $8 per ton	$ 1.92
0.5 E. H. P. year at $ 12	6.00
30 lbs. electrodes at 3 cents per lb.	.90
Miscellaneous	$1.50
	$10.32

In order that blast furnace smelting might cost as much as this, we should have to assume a price for coke of over $7.00 per ton. Such a price actually obtains, or is exceeded, in many localities.

Noble, or Héroult, Ore Smelting Furnace.—At Héroult, California, where coke is costly, electric ore smelting is carried on in a furnace originally designed by P. Héroult, but now modified. The general form and arrangement at present is similar to the Domnarfvet furnace, and a similar circulation of gases is employed to cool the crucible roof, although they are here tapped from the middle of the shaft. The power consumption is said to be[1] only 0.2 hp. year per ton of pig iron and the carbon consumption close to the theoretical amount. Smelting is apparently a commercial success at this plant.

Refining of Pig Iron and Melting in the Electric Furnaces.—There are no technical or practical difficulties in the way of removing carbon, silicon, manganese, phosphorus, sulphur, gases, slag, oxides and other foreign substances in the electric furnace, and one can find substantial evidence in the literature and at steel works, (especially in Germany and America) of such practice in furnaces of the Roechling-Rodenhauser, the Héroult, the Girod, the Stassano, the Giffre, and other types. The principles by which the purification is accomplished are the same as those applied in the processes with which we are more familiar; for example, the blast furnace (as to sulphur only), the Bessemer, open-

[1] The *Eng. and Min. Jour.*, Aug. 6, 1910, page 271.

hearth and puddling furnaces, the crucible process (as to slag, oxides), etc. On the other hand, commercial considerations strictly limit refining in electric furnaces, because carbon, silicon and manganese can be much more cheaply eliminated in the puddling, Bessemer and open-hearth furnaces. Even the removal of phosphorus is cheaper in the puddling furnace and basic Bessemer and open-hearth processes, and just as effective as the present electric processes. Depending upon the proportion of phosphorus present, it requires an expenditure of about 40 to 200 kw. hours to dephosphorize one ton of metal previously melted, besides heavy costs for electrodes, repairs, etc. These expenses give the older processes the advantage in cost under all usual conditions. When it comes to both melting and refining, the situation is still more against electric energy, because at least 400 to 600 kw. hours are required to melt a ton of solid iron or steel, besides the long operation during which other expenses accrue.

Only when melting steel containing costly ingredients which will be oxidized and wasted in the open-hearth furnace—as, for instance, high-priced alloy steels, etc.—do commercial considerations favor the electric melting process with its possibility of melting in a neutral or reducing atmosphere.

Super-refining in Electric Furnaces

These considerations relegate the chief field of electric refining processes to the performance of operations which are beyond the scope of the Bessemer and open-hearth processes, and the most important of these fields are desulphurizing and deoxidizing the bath, and removing from it entangled particles of slag, oxide, etc. The electric processes can accomplish these objects by virtue of their ability to heat a liquid bath of metal in a non-oxidizing or actually reducing atmosphere. In this respect the electric processes resemble the crucible process, but they have two advantages over crucible heating, of which the first is an ability to desulphurize by means of attaining high temperatures, and the second is greater economy of operation. The amount of capital required to install electric furnaces, the large product necessary to obtain economical operation, and the established position of crucible steel in the trade, as well as the capital invested in crucible plants, will probably keep this process alive

for a long time, just as the puddling process has persisted for decades since the development of the Bessemer and the open-hearth process.

The usual super-refining in the electric furnace, of metal previously made in the open-hearth or Bessemer furnace, consists of an oxidizing period, during which the phosphorus is reduced to any desired point, followed by a reducing period during which the sulphur and occluded substances are removed.

Where acid Bessemer steel is super-refined, the necessity for the oxidizing period for the removal of phosphorus is obvious, but where electric super-refining follows the basic open-hearth operation, it would seem as if the oxidizing period in the electric furnace might more economically be replaced by a continuance of the dephosphorization to the desired point on the basic hearth.

Practice in Super-refining.—The metal before leaving the Bessemer or open-hearth furnace is reduced as low as practicable in carbon, silicon, and manganese, but is not recarburized. It is often poured directly into the electric furnace in liquid form, although sometimes the use of an intermediary mixer is advantageous. To the liquid bath in the electric furnace is now added materials for making a basic, oxidizing slag, rich in iron, resembling more the puddling furnace slags than those of the open-hearth. The advantage of such a slag is that iron oxide is not only retentive of phosphorus, but it will also oxidize phosphorus. We have already pointed out that phosphorus must be oxidized in order to be eliminated from the metal and it must also be absorbed by a slag that is retentive of it. A slag that is basic by virtue of lime will retain phosphorus but will not oxidize it. Moreover, iron oxide is a cheaper base than lime, and has the further advantage that the reactions which it produces result in the formation of metallic iron which increase the yield of the process. It is obvious that the metal treated in the electric furnace must begin by being low in carbon, else the oxidizing agents will attack the carbon at this high temperature in preference to the phosphorus. Moreover, if there is much phosphorus to remove, we must use more than one slag, skimming off the first slags as they become so high in phosphorus that they no longer absorb it readily from the metal. Likewise, if the phosphorus is to be reduced from a moderate point to a very low point, we must skim off the first slags formed, because there is a certain ratio of distribution of phosphorus between metal and

slag which prevents a highly phosphorized slag from reducing the phosphorus in the metal to a low point.

After the phosphorus in the metal has been reduced to the desired proportions, the oxidizing slag is removed as completely as possible and then a new slag is formed containing the smallest possible amount of oxides of iron and manganese, and running as high as 70 to 90 per cent. lime. At this point we add carbon to commence the deoxidation of the metal. This is the cheapest agent we can use for the purpose, and as it acts chiefly upon the slag in which it floats, its chief function is to deoxidize this slag and therefore make it more attractive for the oxides in the metal, for there is also a ratio of distribution for oxides between metal and slag similar to the ratio of distribution of phosphorus already mentioned. The carbon deoxidation may be supplemented by the use of silicon, manganese and aluminum, if desired.

Only when both slag and metal are relatively free from reducible oxides (i.e., chiefly oxides of iron and manganese) can the reactions begin whereby the bulk of the sulphur is removed:

1. $C + (Fe.Mn)S + CaO = CaS + Fe.Mn + CO$;
2. $Si + 2(Fe.Mn)S + 2CaO = 2CaS + 2Fe.Mn + SiO_2$.

This point is recognized by the two circumstances that the slag becomes snow-white and that it falls to powder on cooling, both of which are proof of its very low content in oxides of iron and manganese. The presence of calcium carbide is a further indication.

It is this desulphurizing by means of calcium sulphide which is the great advantage of the electric furnace in respect to sulphur removal. In the basic open-hearth furnace also we may reduce sulphur by means of a very basic slag, and by virtue of the ratio of distribution of sulphur between metal and slag. This ratio of distribution depends upon the basicity of the slag, its fluidity, and its volume in reference to the volume of metal, as well as its paucity in iron oxide. These conditions may be maintained to a certain degree in the open-hearth furnace, except only that the heat there is not sufficient to maintain an extremely basic slag in a fluid condition, while the oxidizing conditions there also oppose a low content of iron oxide in the slag. Moreover, the sulphur in the producer gas of the open-hearth process is an important factor, counteracting the removal of the last traces. On these accounts it is ordinarily impracticable to reduce the

sulphur below 0.02 to 0.03 per cent. The presence of manganese, as already noted, assists in the removal of sulphur, because it would seem that manganese sulphide increases the coefficient of distribution of sulphur in favor of the slag. Even in the electric furnace the presence of manganese assists in the removal of sulphur, because manganese sulphide migrates more readily to the slag than does iron sulphide, and therefore tends to bring the sulphur in contact with the lime which makes possible reactions (1) and (2) given above.

As regards the ability of the electric furnace to free the metal from occluded oxides, we need hardly do more than refer to the circumstance already mentioned of the slowness with which these microscopic particles rise to the surface of the liquid metal, commensurate, in some degree with the rising of cream on milk. The quiescent period of deoxidation and desulphurization in the electric furnace produces the conditions which permit of this separation, and the absence of any subsequent deoxidation by means of manganese, silicon, or aluminum removes the liability to the formation of those oxides which might become entangled.

Electric Refining Furnaces

Induction Furnace.—The simple induction furnace is based upon the principle of the ordinary static transformer, whereby alternating electric current is transformed to lower voltage. It was independently developed by E. A. Colby, of the United States, and F. A. Kjellin, of Sweden, whose American rights have been joined under one management. A sectional elevation of the furnace is shown in Fig. 329, in which *CCCC* is the core of an electro-magnet, around one leg of which a coil of wire, *AA*, passes. When an alternating current goes through the coil, *AA*, it sets up an alternating magnetic field in the core, *CCCC*, and this in turn sets up a secondary current in the circle, *BB*, parallel to the coil, *AA*. In other words, an alternating current passing through the coil, *AA*, induces an alternating current in the coil, *BB*, without there being any metallic connection between the two. This is a well-recognized phenomenon in electrical engineering and requires no further comment here. In the furnace operation, the circle, *BB*, is a hollow ring in the brickwork into which melted metal is poured. The resistance offered by this melted metal to the passage of the induced current generates heat which will

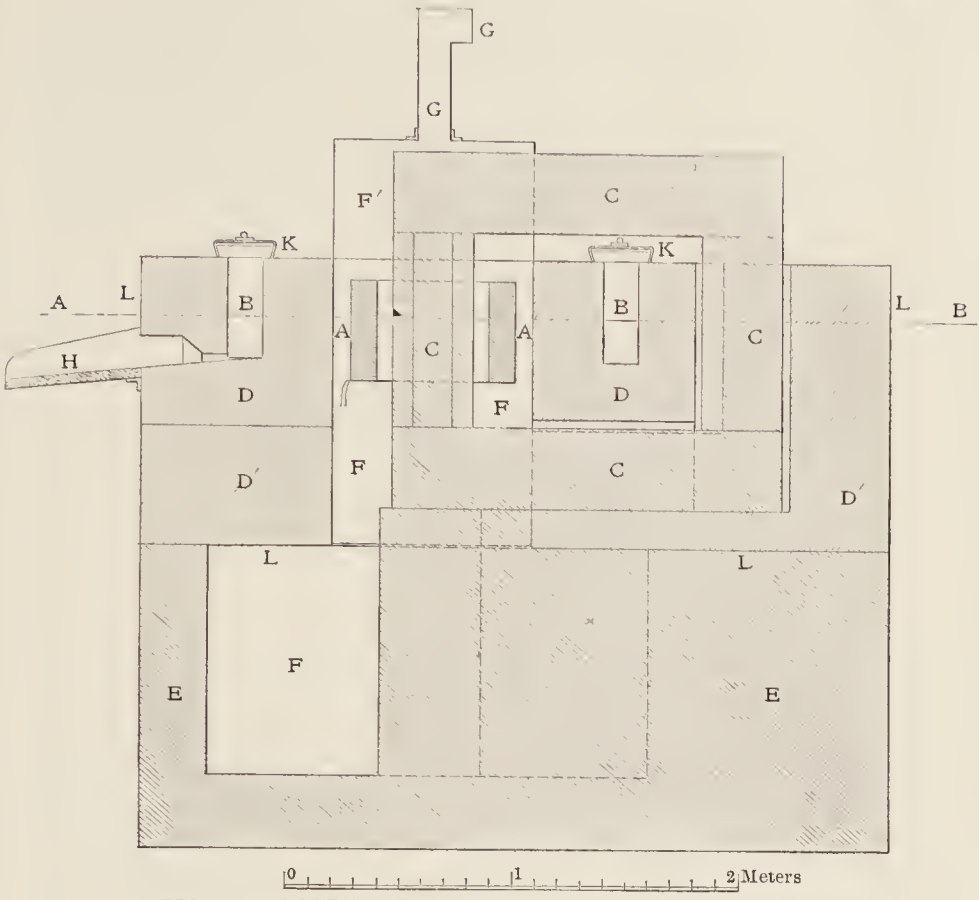


FIG. 329.—SECTION OF KJELLIN INDUCTION FURNACE.

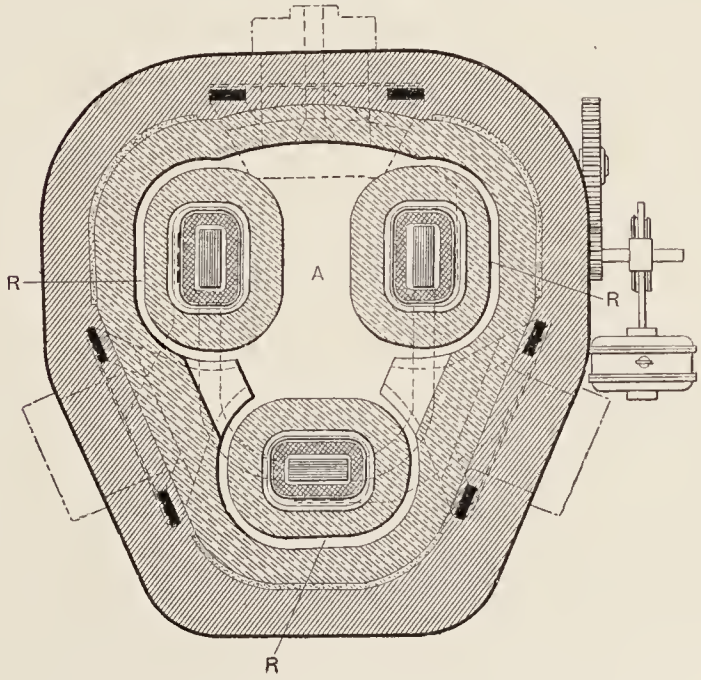
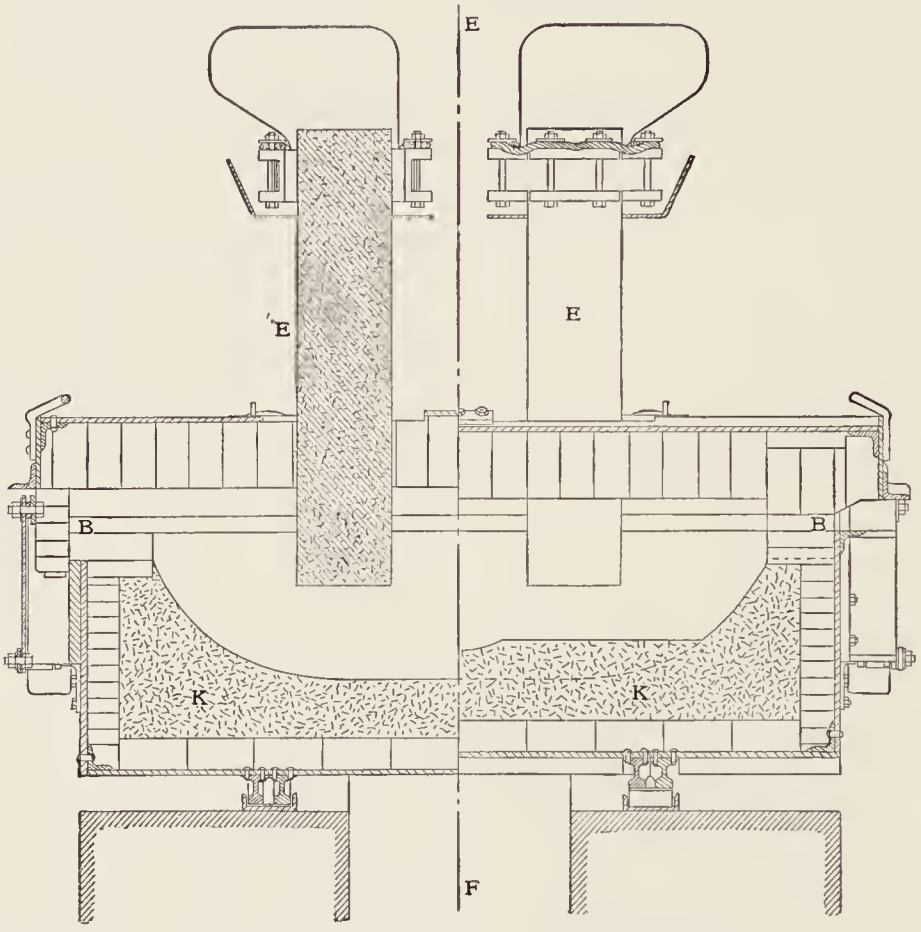


FIG. 330.—ROECHLING-RODENHAUSER FURNACE.

maintain the temperature or raise it to any desired point. The slot, *BB*, is really an annular crucible into which pig iron, steel scrap, iron ore and flux may be charged as if it were an open-hearth furnace, and the operation of steel making is practically the same in principle except that electric heat is employed instead



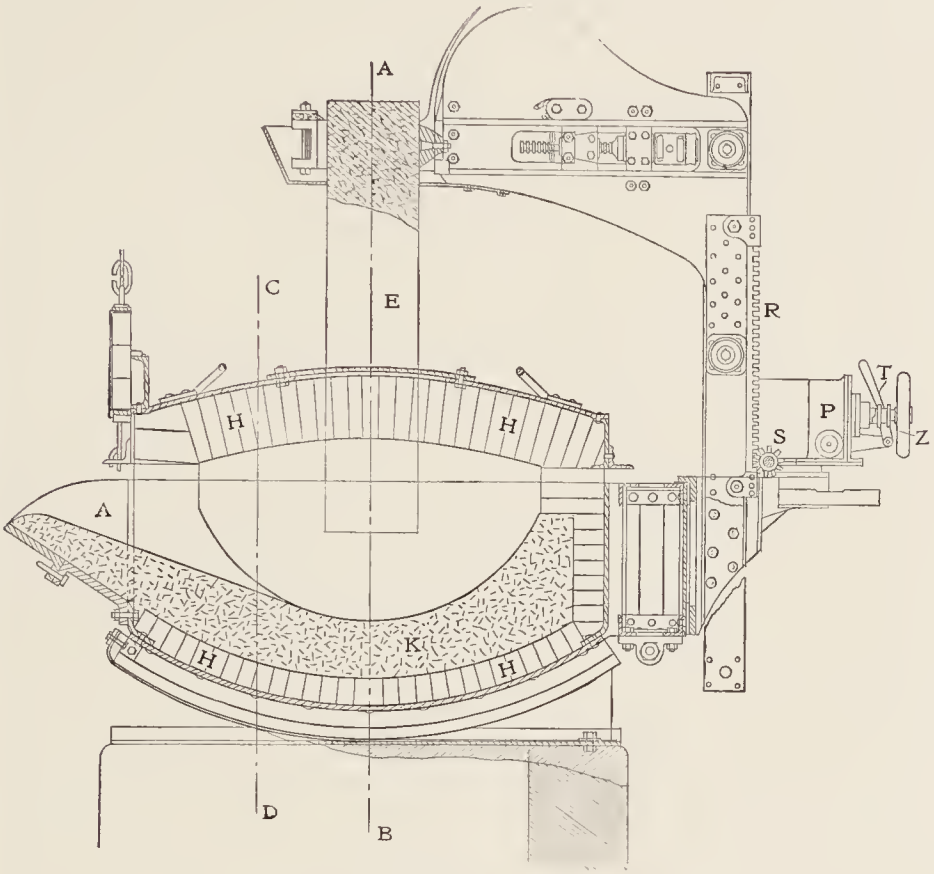
Longitudinal Sections A B & C D

FIG. 331.—HEROULT REFINING FURNACE.

of regenerated gas and air. We may charge solid metal if desired, but, in such a case, it is well to leave a shallow circle of metal in the bottom of the slot, *BB*, after each operation is ended, to serve to carry the induced current during the beginning of the next operation, until the solid charge is melted.

Roechling-Rodenhauser Furnace.—The combination induction furnace is shown in Fig. 330. This is in effect a combination of

three simple induction furnaces, the coils of the metallic baths joining in a central pool. By means of this pool, a more effective refining may be employed, for the pool serves the purpose of a bath upon which slags may be charged, etc. It has also several steel terminal plates imbedded in the lining, which are connected to a few heavy turns of copper placed outside the primary coils,



Transvers Section E F

FIG. 332.—HEROULT REFINING FURNACE.

which collect and feed to the terminal plates the induced current in these turns, thus suppressing magnetic leakage.

Héroult Furnace.—The design and operation of the Héroult steel furnace is even more like an open-hearth than the induction furnace, although here again electric heat is substituted for combustion. The general form of the furnace is shown in Figs. 331 to 332. There are two electrodes of carbon, one of which leads the current to the charge and the other conducts it away. The

electrodes do not touch the charge, but the current arcs from one electrode to the charge, through which it passes, and thence arcs to the negative electrode.

Girod Furnace.—The design of the Girod furnace is very similar to that of Héroult, but electrodes in the bottom carry away the current, instead of double electrodes at the top. See Fig. 333.

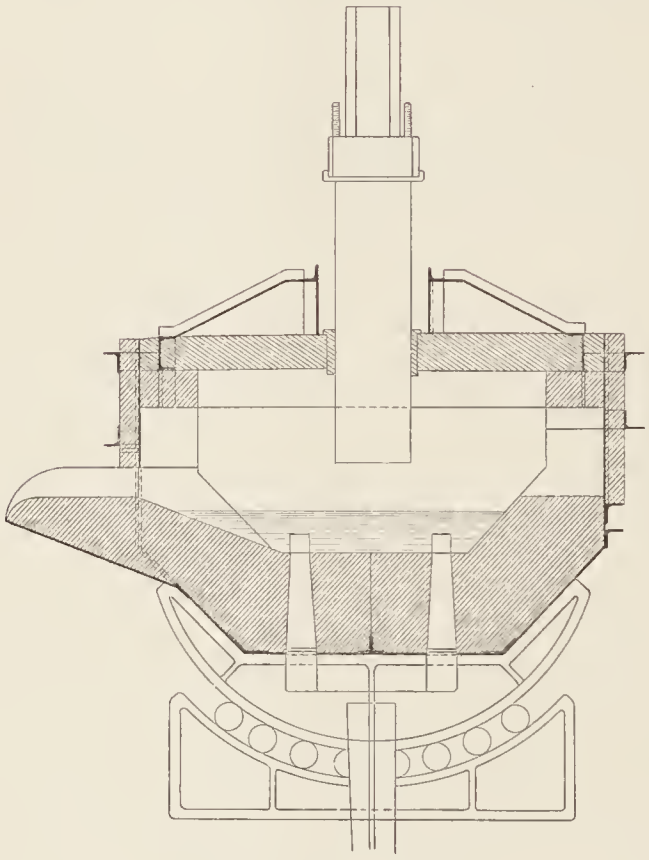


FIG. 333.—GIROD FURNACE.

Electrolytic Refining of Iron

The greatest amount of work on the electrolytic refining of iron has been done by C. F. Burgess, of the University of Wisconsin, who produces an iron that is almost chemically pure, the chief foreign element being hydrogen, whose presence renders the metal very hard and brittle. The hydrogen is driven off by heating the metal to a high temperature, but this is accomplished with the result of vitiating the iron with traces of carbon and sometimes other impurities, for iron has such a great affinity for

carbon that it will absorb it at a red heat from coke, charcoal, and even from gases and oil vapors. Indeed, if a piece of electrolytic iron, or other iron very low in carbon, be heated in contact with steel or wrought iron higher in carbon, there will be a small amount of transfer of carbon from the low- to the high-carbon metal. The same difficulty is met with in melting the metal, and as its melting-point is 1507° C. (2745° F.), there are not many kinds of crucibles that will stand the heat necessary and yet fail to yield carbon, silicon, or some other impurity to the iron. As I understand it, it is this difficulty which has been the chief obstacle in the electrolytic process, for the electrolysis itself seems to be accomplished by Burgess with success and economy. If the cost of the electrolytic product could be brought somewhere near that of Swedish iron and the other very pure forms, it is probable that it would become a commercial commodity on account of its high magnetic permeability, electric conductility and softness.

Electrolytic Process.—In Burgess's process the electrolyte is a mixture of ferrous sulphate and ammonium sulphate and it is kept at a temperature of 30° C. (86° F.). The anode is ordinary wrought iron or steel and the primary cathode upon which the first metal is deposited is a thin strip of sheet iron. The deposited metal sticks so slightly to this that no difficulty is met with in separating them after the operation is finished. The electric current, with a density of from 6 to 10 amperes per square of cathode surface, deposits the dissolved iron upon the cathode with an efficiency of nearly 100 per cent., and cathode plates averaging about three-quarters of an inch thickness are produced in a four weeks' run.

XVIII

THE METALLOGRAPHY OF IRON AND STEEL

Metallography in its larger sense is the description or study of the structure of metals. That branch of the subject which comes under the head of microscopic metallography is, however, the most important because the structure of most metals, especially iron and steel, is discernible only when magnified. We shall see, however, that the observation of structure by eye—known as macroscopic metallography—is not without great value.

Microscopic metallography has now reached that stage of importance where it is viewed almost on a par with chemical analysis and physical testing. In the United States practically every large steel works is well equipped for the microscopic analysis of its product, and important laboratories of the universities and of consulting metallurgists devote much attention to the study. Although only a little more than twenty years have elapsed since the art first received attention, it has advanced so far as to have become by now another and a very serviceable tool in the hands of the expert. I take this opportunity, however, of offering a word of warning: reputations have more than once suffered severely, because of erroneous deduction made from microscopic evidence, and history has shown that those who "rush in where angles fear to tread" are sure to be caught sooner or later. The wise man is he who never bases an opinion upon a sample whose chemical analysis is unknown to him: who never bases an opinion upon a microphotographic negative or print, and who polishes and etches his own specimens, or has these operations performed by some one well known to him and working under his immediate direction. With these precautions the microscope is a very reliable index to an experienced mind.

Preparation of Samples for Microscopic Examination

Samples of iron and steel for microscopic analysis can be cut out of soft samples by means of a hacksaw, lathe, or other machine, and broken out of hard and brittle samples by means of a hammer. A good rule to follow is to have the surface that is to

be polished about 3/8 to 1/2 in. on a side. If larger than that, it requires excessive labor for polishing. It requires about sixteen times as much labor to polish a sample an inch square as to polish one 1/2 in. square, and it requires about sixty-four times the labor to polish one 2 in. square. On the other hand it is not advisable to polish to small an area, because the surface will be liable to convexity and therefore very difficult to get into focus, especially for high powers.

Rough Polishing.—After the proper size of a specimen is obtained the next step is to give its surface a bright mirror-like polish, free from any scratches discernible even with high powers of the microscope (1,000 diameters or so), and this result is achieved with the greatest economy in labor by proceeding by gradual steps:

If the surface contains deep gouges, or marks produced by cutting or breaking it out, it should first be brought to a plane surface by rubbing across a rough file, a grindstone, or an emery wheel. For my own work I much prefer to rub the specimen across a file rather than to put it in a vice and draw a file across it, for I believe the former method produces a more even—i.e., less rounded—surface and therefore conduces to economy of labor in the later operations. It is best to hold the specimen lightly in the fingers and draw it back and forth across the file in a straight line, avoiding any circular motion and therefore having the polishing marks all parallel and straight across the specimen.

When a plane surface has been produced in this way the specimen should be rubbed on a very smooth file. In this operation the specimen should again be held in the fingers and rubbed in a straight line back and forth, and should be turned 90° from the first rubbing so that the marks now made will cut vertically across the first scratches. In this way it is very easy to tell when the scratches made by the first file are entirely eliminated and the operation on the second file should be continued to at least this point no matter how short and faint the old scratches may prove to be. It only takes a minute or two to remove the last scratches on this smooth file, but it would take several minutes to remove them by means of one of the later polishing mediums, and the greatest economy is obtained by having each stage of the operation absolutely complete.

After coming off the smooth file, the specimen is again turned 90°, so that the marks now to be made run in the same direction

as those made on the rough file, and rubbed across a sheet of ordinary 00 emery paper cut to about 3 3/8 in. wide by 9 in. long and pinned with thumb tacks upon a piece of planed, 1/2-inch board. This operation is continued until the last marks from the smooth file are removed.

Fine Polishing.—The polishing then proceeds in the same manner by steps upon French emery paper of gradually increasing fineness, each piece being cut to about 3 3/8 in. by 9 in. and mounted on a smooth board. Of the Hubert brand the grades are designated 0, 00, 000, and 0000.

After the 0000 French emery, the surface is very smooth and bright and is given a final burnishing by rubbing across a piece of broadcloth or baize stretched over a piece of wood, moistened with water and covered with a very thin liquid paste of water and best washed rouge. This should leave the specimen polished as bright as a mirror and free from all scratches. It may be, however, that the eye or a hand magnifying glass would discover microscopic rounded furrows in the specimen. These are due to scratches made in the early stages of polishing, which have not been eliminated, but whose corners have been rounded off by the finer grades of polishing mediums. Never permit a specimen containing these furrows to be used as the basis of any opinion.

Preparation of Rouge.—The best jeweler's rouge purchasable is not good enough for polishing, as it contains very fine particles of dirt and grit which produce scratches in the surface of the specimen during the final stages of the process. It is best washed by the metallographer himself. This is best done upon samples of not more than one teaspoonful of rouge at a time tirred in about a glassful of water in a flat pan or dish until thoroughly wetted. After allowing to settle for about five minutes the water is poured into an ordinary chemist's wash bottle where it is kept until ready for use. The last dregs of the water, containing a good deal of coarse rouge and grit, is thrown away. A little experience soon teaches one to get the maximum amount of good rouge from a sample, without any particles that would produce scratches. The rouge in the wash bottle is protected from dust and dirt and can be poured out of the glass tube on to the broadcloth polishing board as needed. For the preparation of special powders for the very finest grades of polishing, the reader is referred to the references at the end of this chapter.

Precautions as to Polishing.—Do not rub the specimen too

hard on the polishing mediums. This does not produce the desired effect any more rapidly and may distort the structure of the metal so as to lead to erroneous conclusions.

Do not allow the specimen to become heated by the polishing. This is especially true of hardened steel and other heat-treated specimens which may become tempered and so altered even upon gentle heating.

Rub a piece of hard steel over each piece of polishing paper and broadcloth before using it for polishing your specimen. This is to get rid of grit.

Do not lay polishing boards down where dust will get on them, but let them stand with the full height upward inside a closed box or a small closet.

Never form an opinion upon a specimen that retains scratches or polishing marks.

Mechanical Polishing.—Instead of rubbing the specimen across different mediums by hand, we can press them against the emery papers and rouge-cloth mounted upon wooden discs about 8 in. in diameter, revolving at speeds of about 600 r.p.m. This method saves time and the necessary apparatus is very simple to make, or can be purchased complete.[1] Hand-polishing is preferable except upon the rouge, because of the liability to heating the specimens with the higher surface-speed, and to damage of the specimen by having it snatched out of one's fingers.

Developing the Structure for Examination

To develop the structure of iron and steel so as to differentiate between the constituents, four methods are available:

(1) Polishing in bas-relief.
(2) Etching with chemicals.
(3) "Polish attack," and
(4) Heat tinting.

Polishing in Bas-relief.—Where some of the constituents are less durable than others the method of polishing that I have described, upon a soft background, produces a bas-relief, since the softer constituents are worn to a greater depth than the harder ones. The parts thus worn down appear darker than the higher places which reflect the light better. It is by this method that

[1] Consult references 180, 184 and 185.

graphite is best distinguished in pig iron and slag in wrought iron, because the attack by acids is liable to produce other dark spots which may not be readily differentiated. It is by the bas-relief method that F. Osmond developed so beautifully the structure of pearlite shown in Fig. 241. This method has the disadvantage, however, of rounding of the edges of the harder constituents and so causing the softer ones to appear larger than they really are.

Etching with Chemicals—Nitric Acid.—This method is probably the commonest one of developing the structure of steel. Many different strengths of acid are used by different metallographers from 0.1 per cent. up to 20 per cent., and the length of time that is necessary to expose the specimen will depend upon this factor and upon the amount of carbon present. High-carbon steel will require a longer time than soft steel and may take as much as 2 1/2 minutes, although this is very rare. The nitric-acid solutions are usually made with alcohol instead of with water, in order to dry more quickly. Some metallographers prefer to immerse their specimens in the acid for a given length of time, and others prefer to hold the specimen in the hand with the polished surface upward, and then deposit a few drops of the etching fluid upon it with a piece of rubber tubing on the end of a glass rod. In any event it is usually better to etch a shorter time than is estimated as suitable, examine under the microscope, and then etch again if necessary. After every etching it is necessary to wash the specimen off with alcohol and dry as quickly as possible. This drying is best accomplished by absorbing all the liquid left on the surface after the alcohol wash with a piece of soft cloth and then holding in a stream of air. Some metallographers wash the specimen after etching with alkali, and then with water and then with alcohol. Sauveur immerses his specimen in the strongest nitric acid for a few seconds and then places it in a stream of running water, washes with alcohol and dries. As the strong nitric acid puts the steel in a passive state, the length of attack by this method is only momentary, so that it is necessary to repeat it a few times. It results in a very even etching of the surface.

Iodine Etching.—Some investigators use iodine for etching, by rubbing a few drops over the surface until a film covers it, and allowing it to remain until the iodine color has disappeared, after which the iodine is washed off with alcohol and dried. A good iodine solution for this purpose is the ordinary tincture of

iodine diluted with an equal volume of alcohol. It is also well to have an auxiliary solution of about one-fourth this strength for lighter etching work.

Picric Acid Etching.—I have found the 5 per cent. of picric acid in alcohol, which Igevsky used for hardened and annealed steels, very useful also for wrought iron, very low carbon steels, and pearlite.

Polish Attack.—The method of "polish attack" advised and used by Osmond, consists in rubbing the specimen upon a piece of parchment stretched over a piece of soft wood and moistened with a 2 per cent. solution of ammonium nitrate. This method gives very beautiful results in Osmond's hands and is especially valuable for developing the structure of martensite, troostite, pearlite, and sorbite.

Heat Tinting.—Heat tinting consists in warming the steel until it becomes oxidized. The different constituents are oxidized at a different rate and so may be distinguished from one another. It is most serviceable in distinguishing the phosphide of iron from the carbide, for by heating until the carbide is red, the phosphide (Fe_3P) will be yellow. The phosphorus eutectic may be distinguished from pearlite in the same way, because the former will be yellow when the latter is blue. The heat tinting must be accomplished in such a way as not to expose the metal directly to a flame. The simplest method is to put the specimen upon an iron plate heated from beneath.

Microscope and Accessories

It is hardly desirable to describe here the different forms of microscope and accessories used for metallographic work, as the manipulations cannot well be learned, except by practice, and the catalogues of the manufacturers of scientific instruments of all iron-producing countries now give full data. A photograph of a common illuminating device, microscope and camera, is shown in Fig. 338. Those who expect to take up the subject should procure a book upon it and study it much more fully than we have space for here. The chief difference between the microscopic examination and photography of iron and steel, and of biological specimens, botanical specimens, thin rock sections, etc., arises from the non-transparency of the metal. It is necessary to illuminate them from above, since we cannot cause the light to

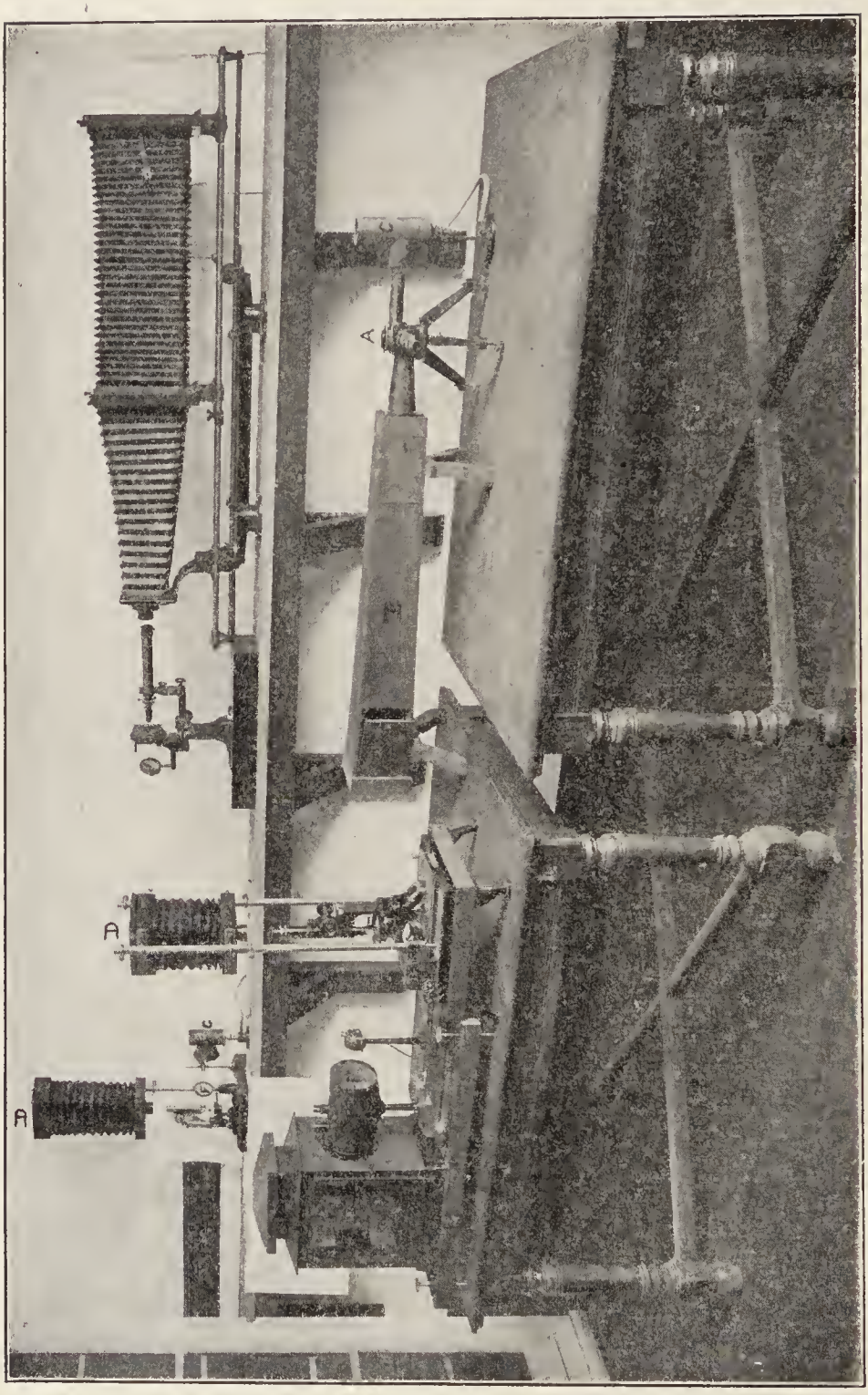
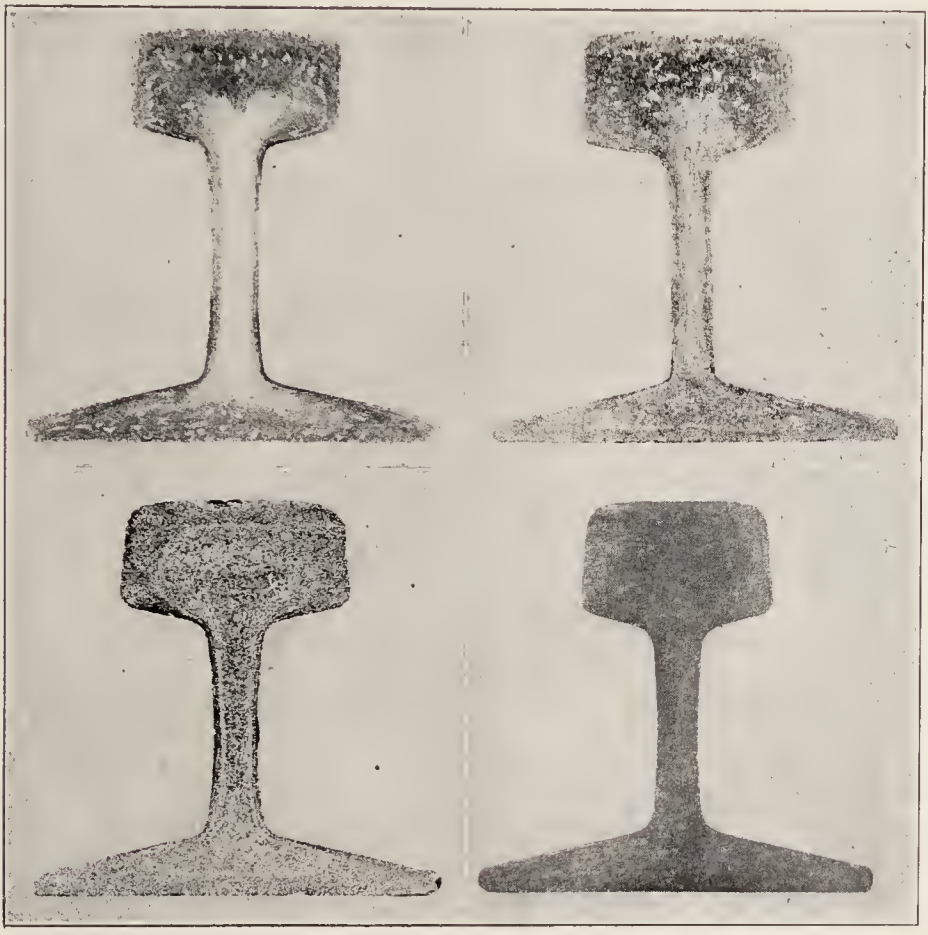


FIG. 338.—PART OF THE MICROPHOTOGRAPHIC APPARATUS IN THE METALLOGRAPHIC LABORATORY, DEPARTMENT OF METALLURGY, COLUMBIA SCHOOL OF MINES.

A, Le Chatelier microscope; B, Le Chatelier camera; C, Welsbach light and stand; D, Sauveur camera; E, electric arc illumination; F, condenser for light rays.

pass through the specimen and into the instrument. This necessitates special forms of illuminators and powerful lights. For magnifications of about 500 diameters, the Welsbach mantle gives sufficient illumination. The Nernst lamp is also very useful, but for very high powers it is necessary to use the electric arc lamp. This introduces especial difficulties, because the focus



FIGS. 339 TO 342.—RAILS ETCHED FOR SEVERAL HOURS WITH DILUTE HYDROCHLORIC ACID.
FIG. 339.—RAIL WITH SOFT INTERIOR; ROLLED FROM TOO NEAR TOP OF INGOT.
FIG. 340.—RAIL WITH BLOWHOLES AND SOFT INTERIOR.

which gives good definition to the eye by means of the arc light will be blurred upon the photographic plate. The use of a light-yellow screen in front of the light assists in this difficulty, but a good deal of experience is required to get good results. A mercury light avoids this difficulty.

Magroscopic Metallography

An experienced eye may get a very good idea of the size of crystals in iron and steel by examining a freshly broken fracture, and this is one of the branches of magroscopic metallography. For the most accurate results, however, it is not as good as microscopic examination.

It is also possible to get other information by etching a polished surface for many hours with dilute hydrochloric acid. For this purpose the polishing need only go as far as the commercial 00 emery paper, following the smoother file. In this way the center of ingots, because of their looser texture, will be eaten away much more rapidly, and this will be evident to the unaided eye. Also the interior of sections of large area will be attacked more than the outside, which has become harder through the work of rolling. Some blowholes, which cannot be seen by eye or have been partially welded up, may often be discovered, because the etching action is more severe in their neighborhood, and the same is true of spots where segregation has occurred. After etching and examination, permanent records may be kept of the indications by covering the etched surface with printer's ink and then pressing it with a letter file on to a piece of cardboard or heavy paper. A few examples of records made in this way are shown in Figs. 339 to 342.

XIX

METALLURGICAL FUELS

Metallurgical fuels may for convenience be divided into three classes: (1) solid fuels, which include wood, charcoal, anthracite anthracite coal, bituminous coal and coke; (2) liquid fuels comprising chiefly crude petroleum and its products and tar, and (3) gaseous fuels, including natural gas, producer gas, water gas and special manufactured gases.

Wood.—Wood burns rapidly with a long flame and is therefore adapted for reverberatory furnace heating, but requires a good deal of labor for firing. The flame from wood has the advantage of being relatively free from sulphur which is a harmful impurity in the flame from bituminous coal. In Table XXXV is shown Gruener's Classical Classification of Solid Fuels, from which it will be observed that the volatile matter of wood is relatively very high and that the fixed carbon is relatively low in comparison with the other solid fuels.

Charcoal.—Charcoal is made from wood by driving off the volatile matter and leaving the fixed carbon. This process of manufacture which is known as "charring" or carbonizing, is accomplished by heating the wood out of direct contact with the air. The resulting product is a porous, black, non-lustrous material, pulverulent, without strength. It consists chiefly of carbon with traces of residual volatile matter and small amounts of ash, the latter representing the inorganic solid matter initially contained in the wood. Charcoal burns substantially without flame, and is therefore inapplicable to reverberatory and similar furnaces, but is valued in direct-contact furnaces, such as crucible furnace, cupolas, blast furnaces, etc., on account of its porosity and also its relative freedom from objectionable impurities, such as sulphur and phosphorus. The lack of strength of charcoal limits its usefulness in cupolas and blast furnaces because it cannot support a heavy burden of superincumbent material. It will be remembered that the solid fuel is the only unmelted material below the melting zone of blast furnaces and cupolas, and that it therefore has to support as much of the weight of

TABLE XXXV GRUNER'S CLASSIFICATION

Name of fuel	Chemical composition				Volatile matter					Fixed carbon (coke)	
	C	H	O	Ratio O:H	Total	Gas liquor	Crude tar	Gas	%	Structure	Lustre
Cellulose	44.44	6.17	49.39	7					28–30	Pulverulent	Dull.
Wood	50–51.75	6–6.3	44–41.95		70–65	46–41.4	5.5–7.4	18.4–17.5	30–35	Pulverulent	Dull.
Peat	58–63	6–5.5	36–31.5	6–5					35–40	Pulverulent	Dull.
Brown Coal	65–75	6–4	29–21	5	60–50	20–15	16–14	24–21	40–50	Pulverulent	Often lustrous.
Bituminous Coal: Dry, long flame, non-caking (splint).	75–80	5.5–4.5	19.5–15	4–3	50–40	12–5	18–15	20–20	50–60	Pulverulent or slightly coherent.	
Bituminous Coal: Fat, long flame. Gas coal.	80–85	5.8–5	14.2–10	3–2	40–32	5–3	15–12	20–17	60–68	Caked, but very friable.	
Bituminous Coal: Fat, properly so-called, steam furnace coal.	84–89	5–5.5	11–5.5	2–1	32–26	3–1	15–10	16–15	68–74	Caked, moderately compact.	
Bituminous Coal: Fat, long flame, coking coal.	88–91	5.5–4.5	6.5–4.5	1	26–18	1–1	10–5	15–12	74–82	Caked, very compact, little friable.	Lustrous.
Bituminous Coal: Lean, anthracitic coal.	90–93	4.5–4	5.5–3	1	18–10	1–0	5–2	12–8	82–92	Fritted, or pulverulent.	
Anthracite	93–95	4–2	3	1–0.75	10–8				90–92	Pulverulent	Lustrous.

the material in the shaft as is not held up by the pressure of the blast. Charcoal is used in some iron blast furnaces of small size because of its purity. This is especially true in Sweden, where the advantage of pure iron ores would be to some extent nullified if an impure material like coke were used for smelting.

The manufacture of charcoal is a very simple process, and consists in a slow combustion of the gases which the wood gives off when heated. The process may be carried on in heaps or kilns. In the former practice, the wood is piled up in a regular heap and covered on all sides with earth and sods. Openings are left at the bottom for the admission of a small amount of air and the burning is started by introducing fire at these points. The admission of air thereafter is regulated with great care to the different parts of the heap, so that the gases will slowly burn without there being much fixed carbon oxidized at the same time. The burning occupies many days, and then the heap is torn down and the charcoal is ready for use. Instead of burning in heaps, the wood may be piled in kilns, which have the advantage of permanency. In the latter case, we may carry away the gaseous products of combustion of the charring operation and separate many valuable by-products, such as wood tar, wood alcohol, acetic acid, etc.

Peat, Lignite, Etc.—Peat, lignite, brown coal, etc., represent stages in the natural carbonization of wood to coal in the bosom of the earth. In the majority of cases, these fuels are too impure and too high in ash to be burned on grates. They are sometimes converted into gas in gas producers, and they are often crushed, washed and agglomerated into briquettes, which makes an admirable substitute for bituminous coal and is rapidy growing yearly in the amount used.

Bituminous Coals.—On account of the volatile matter in bituminous coals, they burn with a flame, and are therefore well adapted to use in reverberatory furnaces. The richest in gas are often used for the manufacture of illuminating or city gas, by a simple process of driving off volatile matter by means of heat, but this is a too expensive gas to use ordinarily for metallurgica purposes. Some of the bituminous coals on being heated soften and swell as they give off the volatile components. The softening is sufficient to cause these coals to cake together under the pressure of their own weight, and to consequently form porous, coherent masses of a silvery-gray material, known as coke, which

contains only traces of residual volatile matter, together with ash, representing chiefly the inorganic matter originally contained in the coal. The chief chemical constituent of coke is carbon, amounting often to 87 or more per cent. of the mass. Coke bears approximately the same relation to bituminous coal that charcoal does to wood.

Coke.—Coke is made by distilling the volatile matters from bituminous coal; this distillation takes place in chambers in which only enough air is admitted to supposedly burn the volatile matters, or else in chambers from which the air is excluded completely. The chambers into which a limited amount of air

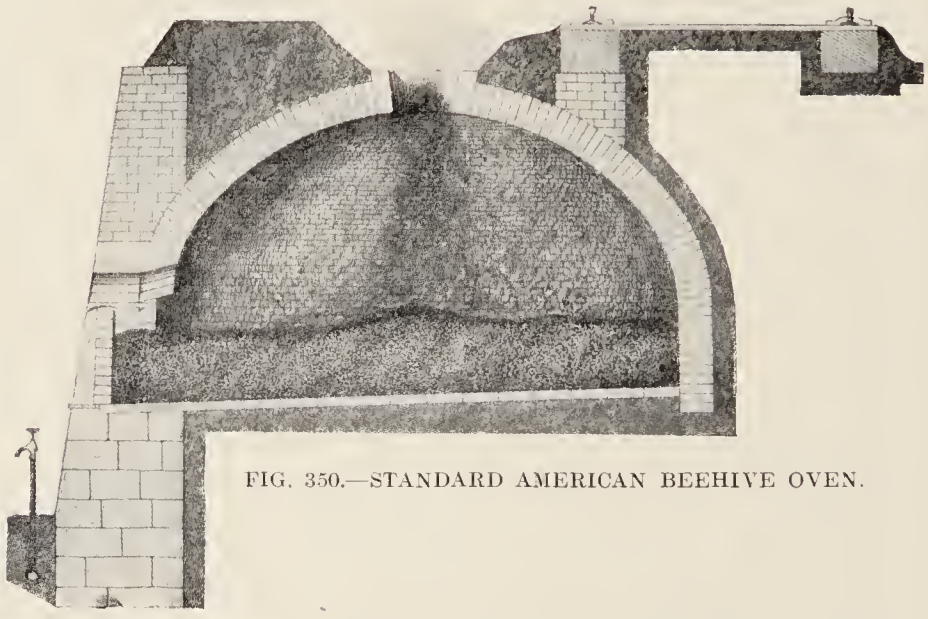


FIG. 350.—STANDARD AMERICAN BEEHIVE OVEN.

is admitted are called "beehive ovens", on account of their form, which is shown in Fig. 350. The chambers into which no air is admitted are known as "retorts", of which a cross-section is shown in Fig. 351. In Europe and England, the retort oven is commoner, but America makes more coke in beehive ovens, which is a far more wasteful method, since only 66 per cent. of coke is obtained from a ton of coal, and no "by-products"; whereas, in retort ovens, we obtain a yield of 75 per cent. of coke and also by-products consisting of tar, ammonia, excess gas, etc., equal in total value to about one-third of the value of the coke. In the United States there are some 104,000 beehive ovens, producing, in 1910, an average of 376 tons of coke each per year; and about

4000 by-product ovens, producing, in 1910, an average of 1762 tons of coke per year. The total production of by-product ovens was 17 per cent. of all in the United States in 1910.

Coking in Beehive Ovens.—The crushed coal is poured into the

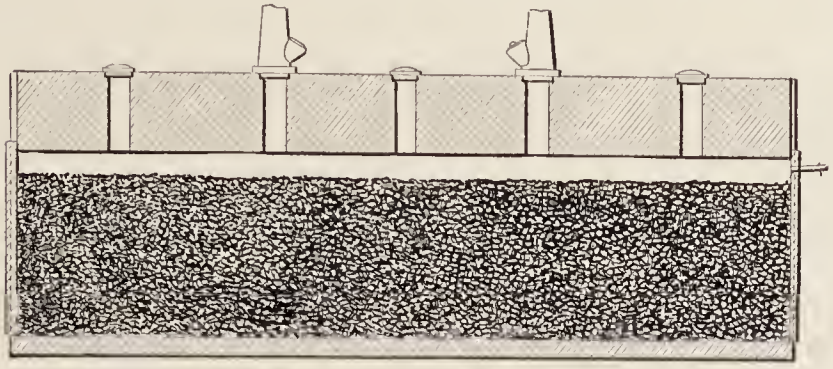


FIG. 351.—HORIZONTAL SECTION THROUGH A RETORT OF A BY-PRODUCT OVEN.

oven through the "eye" at the top, and carefully levelled. Combustion is started at the middle of the top circle of coal, and gas begins to be distilled off by the heat; air is admitted through the arch of the lower door, and flame soon fills the dome and sends a black, sooty smoke out of the eye. The heat from the

FIG. 352.—BATTERIES OF BEEHIVE OVENS.

flame distills the volatile matter from the coal, advancing layer by layer from the top; this causes the coal to swell and rise slightly. At the end of the coking a five-ton charge of coke 28 in. thick will have risen to 34 in. thick. When distillation is complete to the

bottom of the charge, the combustion is stopped by quenching the coke with a stream of water, this action taking place inside the oven itself in order that air may not oxidize the surface of the coke and dull its silvery color. The coke breaks up into long pieces, as shown in Fig. 353. A small amount (say 2 to 2 1/2 per cent.) of fine particles, or "breeze," is formed which cannot be marketed.

Coking in Retort Ovens.—In retort ovens the coal is completely enclosed during distillation, which accomplishes three purposes: (1) it enables the gas distilled from it to be led off into by-pro-

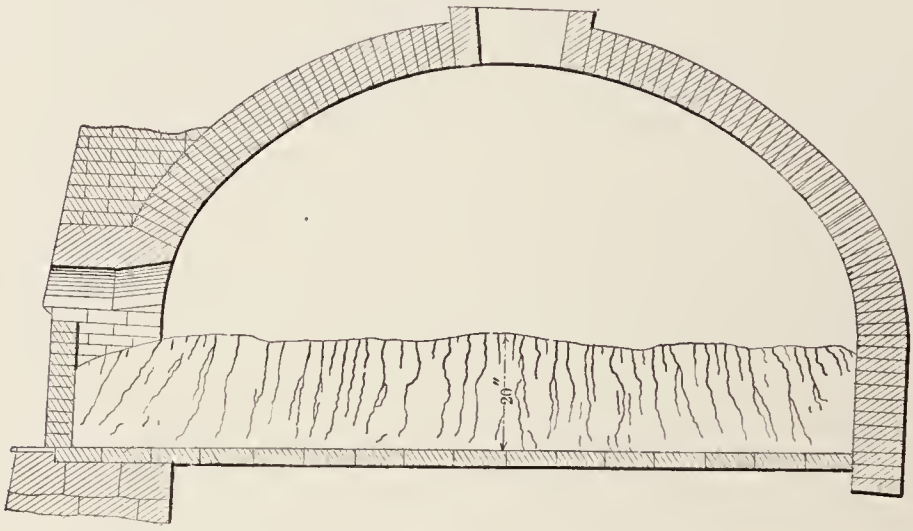


FIG. 353.—STRUCTURE OF BEEHIVE COKE

duct-saving apparatus; (2) it protects the fixed carbon in it from contact with air, which would burn it and reduce the yield, and (3) it puts it under greater pressure during the swelling operation, so that some coals which will not cake into a coherent mass in beehive ovens, will make good strong coke in retorts. The retorts are made of fire-brick, and are heated by burning gas outside of them on three sides. Good coking coals will yield from 5000 to 12,000 cu. ft. of gas per ton. In the beehive oven this is all burned; in retort ovens we burn about one-half of it to produce the heat required for the coking operation, and the remainder is available for sale, or other purposes. In all the retort ovens of the United States in 1910, an average of nearly 3000 cu. ft. of excess gas was obtained per ton of coal used; together with about 7 gal. of tar, and ammonia products in value equal to over 40

cents. The total value of by-products recovered is equal to about one dollar per ton of coal coked.

Surplus Gas Obtained.—The analysis of the gas given off by the coal will vary with the time of coking—that is, the first gas distilled off which is given up more readily, will be richer than that given off later. This is shown by Table XXXVI.[1]

From these figures it will be noticed that the coal also parts with its volatile matter more freely at first—there is more gas given off per hour; secondly, the components of the gas which

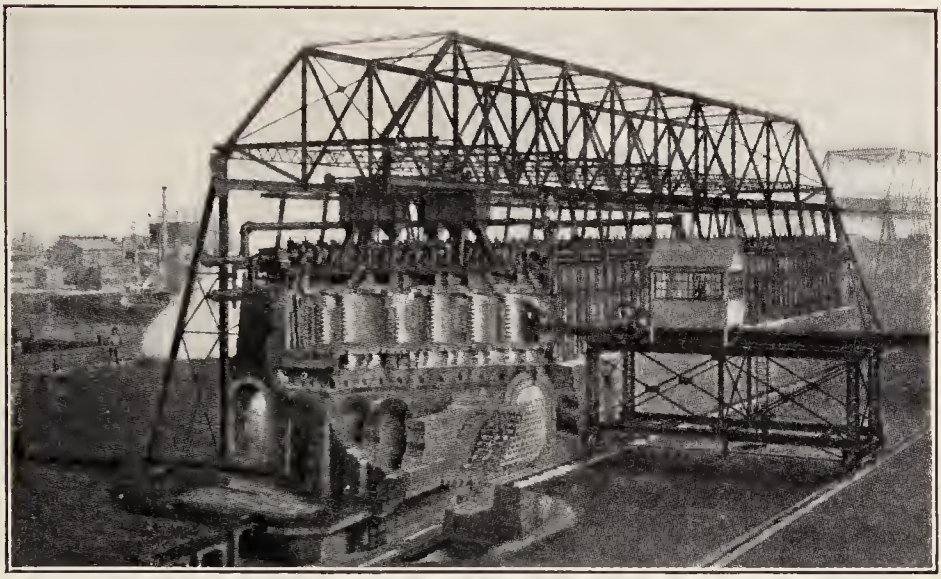


FIG. 354.—OTTO-HOFFMANN BY-PRODUCT, OR RETORT, COKE OVENS.

give the most illuminating power (CmHn) are relatively higher in the gas first given off than in the later gas, and therefore the candle-power of the gas decreases as coking progresses; thirdly, that the calorific power of the gas decreases also, but not at so rapid a rate as the candle-power, especially excepting the last few hours of the operation. Now, if all the gas distilled off in coking a charge of coal was stored in a reservoir it would not be rich enough to use for illuminating purposes for cities, but, if we should store the first gas given off in one reservoir, and the later gas in another, we would have a supply of sufficiently rich gas and a supply of poorer gas. This admirable arrangement, a result of the genius of Dr. Schniewind, is in fact adopted at

1 Taken from Dr. F. Schniewind's paper on the "Production of Illuminating Gas from Coke Ovens," read before the Gas Section of the Engineering Congress at Glasgow.

TABLE XXXVI.—THE ANALYSIS OF GAS GIVEN UP BY COAL DURING COOLING

Hours after charging.	Analysis of gas produced.							Specific gravity of gas from sheet 18	Caloric value of gas produced	Candle power of gas not freed of CO_2	Gas produced during each hour—per long ton of dry coal. Cubic feet	Heat value of gas produced during each hour—per long ton of dry coal B. H. U.	Illuminating Value of gas not freed of CO_2 produced during each hour—per long ton of dry coal. Candle feet
	Cm Hn.	CH_4.	H_2.	CO.	CO_2.	O_2.	N_2.						
1	5.8	40.3	34.3	6.8	3.9	0.2	8.7	.552	707	18.4	413	292,000	7,599
2	5.8	41.2	33.6	6.7	3.8	0.3	8.6	.547	707	18.4	333	236,000	6,127
3	5.8	41.8	34.0	6.5	3.7	0.3	7.9	.539	736	18.4	295	217,000	5,428
4	5.7	41.5	34.1	6.3	4.2	0.4	7.8	.555	699	16.2	312	218,000	5,054
5	5.7	41.5	34.8	5.8	3.9	0.3	8.0	.539	709	15.4	347	246,000	5,344
6	5.4	40.7	36.1	5.7	3.7	0.4	8.0	.527	703	14.4	357	251,000	5,141
7	5.4	39.6	37.6	5.8	3.5	0.4	7.7	.515	693	13.8	342	237,000	4,720
8	5.2	38.8	39.0	5.7	3.4	0.3	7.6	.502	683	14.5	350	239,000	5,075
9	5.0	37.8	40.2	5.9	3.3	0.3	7.5	.492	671	13.7	386	259,000	5,288
10	4.9	37.4	41.2	5.9	3.2	0.3	7.1	.486	666	13.3	344	229,000	4,575
11	4.9	37.0	41.5	6.2	3.2	0.3	6.9	.484	667	13.2	324	216,000	4,277
12	4.8	36.5	42.0	6.3	3.3	0.3	6.8	.482	666	13.2	362	241,000	4,778
13	4.7	36.2	41.9	6.1	3.4	0.4	7.3	.485	672	13.0	363	244,000	4,719
14	4.5	35.7	41.9	6.2	3.5	0.3	7.9	.485	665	12.3	337	224,000	4,145
15	4.4	35.3	42.1	6.2	3.3	0.4	8.3	.483	638	12.1	362	231,000	4,380
16	4.1	34.9	42.4	6.3	3.3	0.4	8.6	.478	624	11.9	364	227,000	4,331
17	3.8	34.7	42.9	6.5	3.0	0.4	8.7	.478	642	11.9	318	204,000	3,784
18	3.7	34.7	42.9	6.6	3.2	0.4	8.5	.477	628	11.8	360	226,000	4,248
19	3.5	35.2	42.6	6.5	3.2	0.4	8.6	.478	623	11.1	345	215,000	3,829
20	3.4	35.1	42.7	6.5	3.0	0.4	8.4	.473	624	10.6	330	206,000	3,498
21	3.2	35.4	44.0	6.5	2.7	0.4	7.8	.458	624	11.0	346	216,000	3,806
22	3.1	34.8	45.4	6.3	2.5	0.4	7.5	.447	625	10.8	344	215,000	3,715
23	2.8	34.1	46.8	6.1	2.4	0.4	7.4	.434	608	10.3	396	241,000	4,079
24	2.5	32.3	48.7	5.9	2.2	0.4	8.0	.425	583	10.3	378	221,000	3,893
25	2.0	30.3	50.5	5.7	2.0	0.3	9.2	.415	556	9.0	320	178,000	2,880
26	1.5	26.8	54.5	5.5	1.8	0.3	9.6	.390	534	7.8	294	157,000	2,293
27	1.3	22.7	59.9	5.4	1.5	0.3	8.9	.361	510	6.3	286	146,000	1,802
28	1.0	19.2	64.0	5.4	1.3	0.3	8.8	.343	469	4.5	275	129,000	1,237
29	0.7	16.9	66.2	5.4	1.1	0.3	9.3	.341	456	3.8	228	104,000	866
30	0.6	15.2	66.4	5.6	0.8	0.2	11.2	.328	440	3.7	168	74,000	622
31	0.5	13.3	66.3	5.8	0.7	0.1	13.3	.330	389	3.8	144	56,000	547
32	0.4	12.0	66.2	6.3	0.8	0.1	14.2	.330	362	3.6	127	46,000	457
33	0.4	10.8	66.2	6.6	1.0	0.2	14.8	.335	362	3.5	94	34,000	329
34	0.2	9.6	66.7	6.4	1.3	0.2	15.6	.338	565(?)	2.5	46	26,000	115
										Total,	10,390	6,501,000	122,981

several by-product coke plants, the rich gas being sold to cities for illuminating purposes, and the poorer gas used for heating the retorts in the coking operation. Before either gas is used, however, it is freed from tar and ammonia. When retort coke is made at metallurgical works, the surplus gas may be used in open-hearth furnaces, or in heating furnaces at the rolling plant, or burned in gas engines for the production of power. When using

this gas in furnaces, the high content of hydrogen causes some difficulty in burning out the brick-work unless care and experience is employed. Failures on this account have been frequent, but the possibility of success is proven by practice in Germany

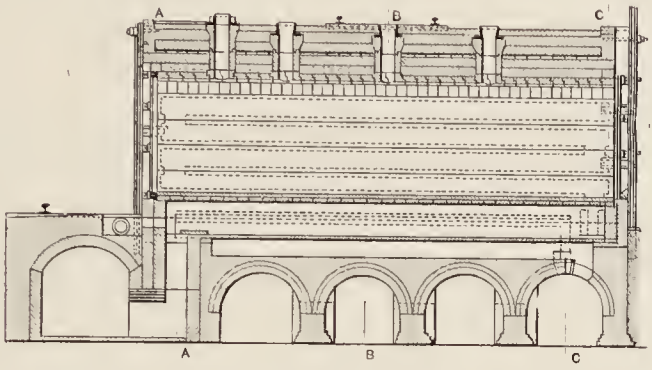


FIG. 355.—LONGITUDINAL SECTION OF SEMET-SOLVAY RETORT COKE OVEN.

and elsewhere, although the life of side-walls and roof is shorter when coke oven gas is used than is the case with natural gas producer gas or oil.

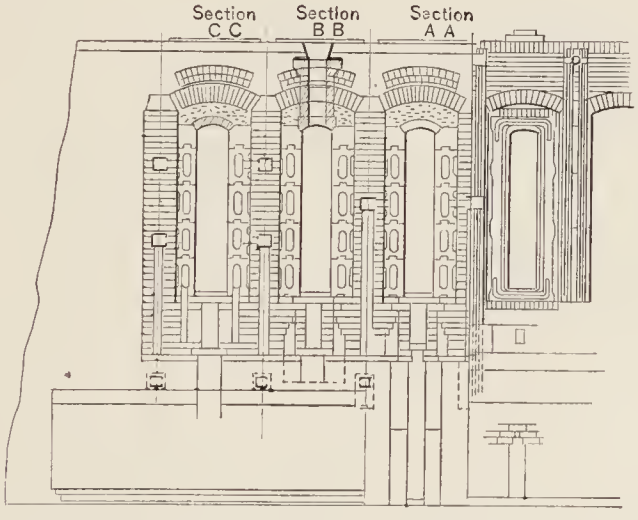


FIG. 356.—TRANSVERSE SECTION OF SEMET-SOLVAY OVEN.

Desiderata in Retort Coke Ovens.—The desirable features of retort ovens are:

1. Uniform heating in all parts of the retort in order that the operation may not be unduly prolonged or the coal unevenly coked. On account of the length of the retorts, this feature has been secured only after some failures and much experimenting by the

pioneers of the art. It is now secured in the prominent types of ovens by three means:

a. Uniform draught in all the flues;

b. Effective regulation of combustion at all points;

c. Shortest possible passages for the burning gases.

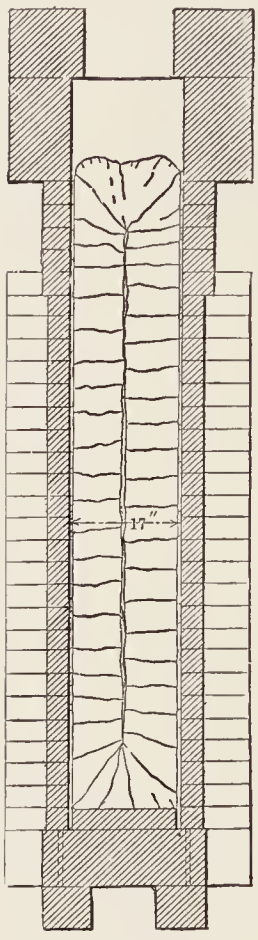


FIG. 357.—CROSS-SECTION OF RETORT.

Structure of By-product Coke.

2. Rapid conduction of heat through the retort walls to the coal. This is secured in various ways:

d. Thin retort walls; but this is qualified to some extent by the third desirable feature mentioned below.

e. High combustion temperatures; this is obtained in many cases by regenerating the air, as in the open-hearth furnace.

3. Strong retort walls to resist the pressure of the swelling of the coal.

4. Large output. This is obtained chiefly by rapid conduction of heat to the coal, and it is a very desirable feature, because retort ovens are very costly to construct, and this heavy overhead expense must be met by large product.

A beehive oven will cost normally not more than $300 erected, while each retort of a by-product plant will cost from $2000 to $3500, which will be raised to $4500 to $7000 including the by-product-saving apparatus. (f) Simplicity of operation and (g) use of mechanical devices are other means by which the output is increased, and also labor costs decreased.

5. Economical heating.—This is obtained by recovering the waste heat in the outgoing products of combustion by regeneration or recuperation, by uniform heating, by effective regulation of combustion, and by complete combustion; i.e., absence of smoke. All of these desiderata are of minor importance compared to rapid conduction of heat through the retort walls already mentioned.

6. Economy in Repairs.—This is another very desirable feature, because the repairs are not only a large factor in the cost

of coking, but time used for repairing reduces output. The means by which this economy is most commonly secured are:

h. Ready accessibility of all parts, for renewal and inspection

i. Simple and strong construction.

j. Avoiding damage to one part of the oven by the operation of another; for example: if the regenerators are placed underneath a heavy weight of brick, their expansion and contraction

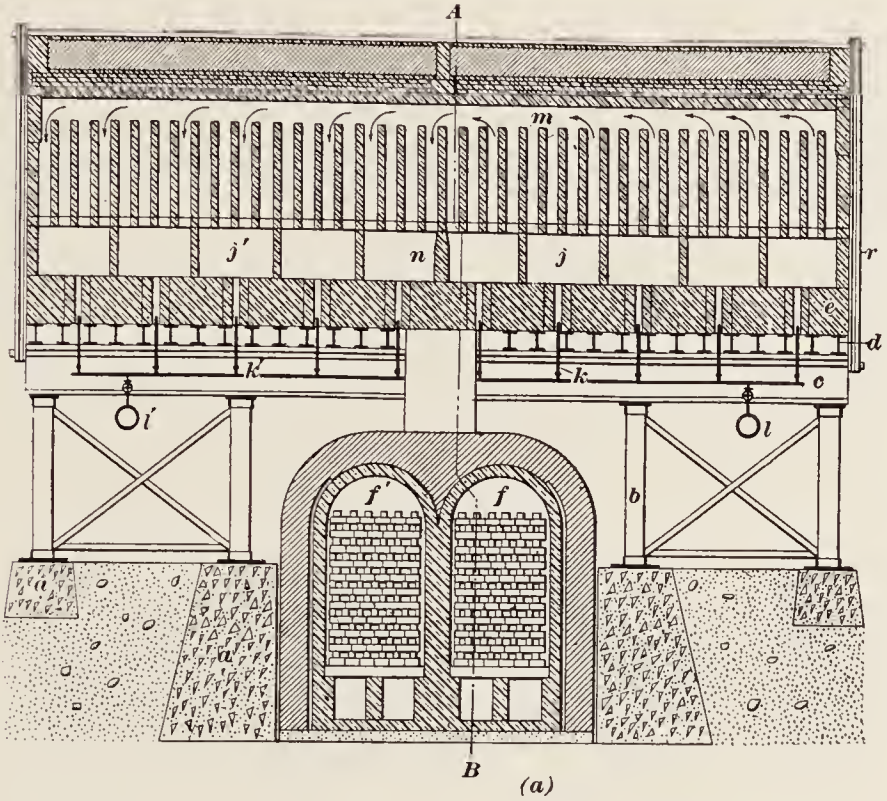


FIG. 358.—THE OTTO-HOFFMANN COKE OVEN. (SCHNIEWIND TYPE).

damages the brickwork above, and the weight of the latter brings a burden on the regenerative chambers while they are hot, and therefore weak.

Different types of retort ovens have been devised to secure these desirable features, but space is not available here to describe them in detail. The following ovens are in use in the United States:

Semet-Solvay	1387 ovens.
United Otto	2104 ovens (Otto-Hoffmann type).
Rothenberg	307 ovens.
Koppers	280 ovens.

Producer Gas.—If air be blown through red-hot carbon the following reaction takes place:

$$C+2O=CO_2;$$

but if the bed of fuel is deep, the carbon dioxide enters into a further reaction, as follows:

$$CO_2+C=2CO.$$

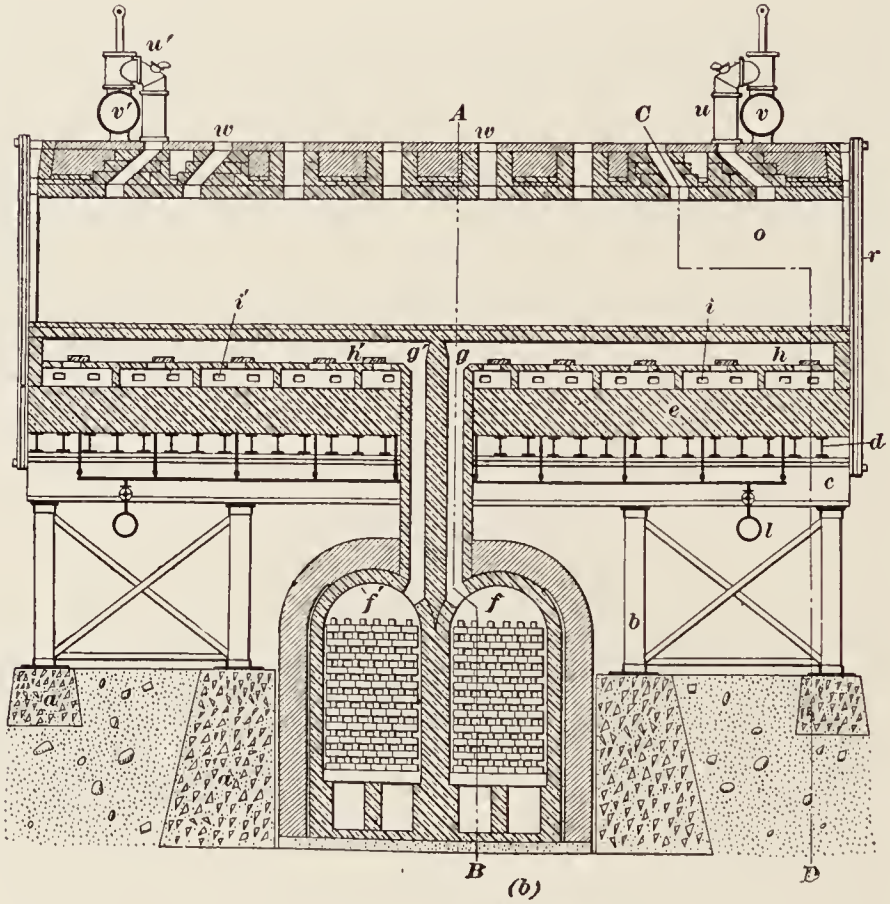


FIG. 359.—OTTO-HOFFMANN OVEN.

In other words, if air be made to blow through a deep bed of red-hot carbon, there will be produced carbon monoxide gas which has combustible value:

$$CO+O=CO_2 \text{ (generates 68,040 calories).}$$

Producer gas for open-hearth and reverberatory furnaces is usually thus made from bituminous coal, because the hydrocarbons contained in this coal enter into the gas and thus give it illuminating power, which makes it much more efficient in the furnace,

because the heating takes place by radiation chiefly. Such a gas will contain 3 to 5 per cent. of hydrocarbons, 20 to 25 per cent. of CO, 55 to 60 per cent. of nitrogen, and 2 to 8 per cent. of carbon dioxide.

The two latter components produce no heat and are therefore worse than useless, because they carry heat away from the furnace up the chimney stack. The nitrogen comes from the air, of course, but the CO_2 is theoretically absent. Its presence

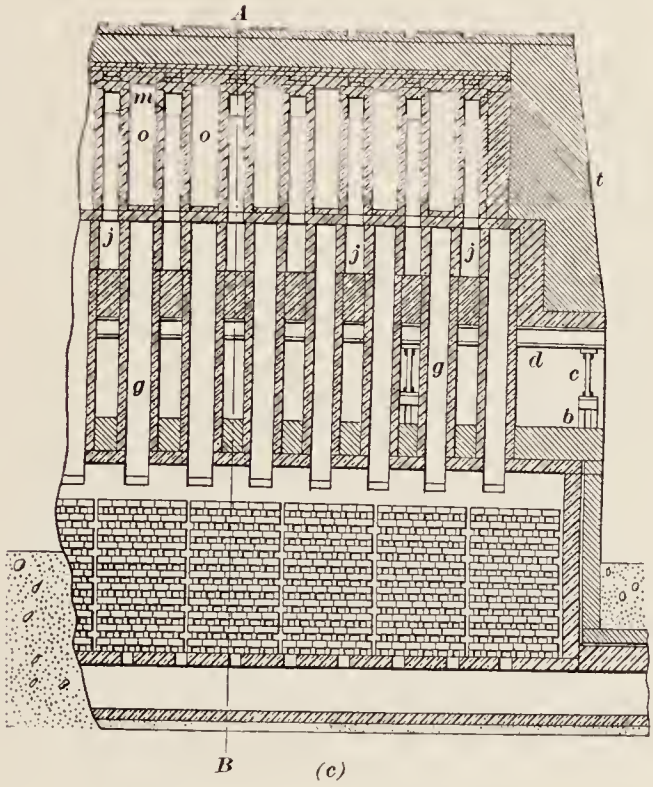


FIG. 360.—OTTO-HOFFMANN OVEN.

is due to irregularities in the gas producer operation, such as vertical channels forming in the bed of fuel, up which the CO_2 gas passes without being brought into contact with carbon; or the rapid passage of the gas does not permit time for the reactions to be completed; or irregularities in the fuel bed, whereby the fuel will be red-hot much higher on one side than on the other.

The air is usually blown through the fuel by means of a steam jet, which results in a certain amount of steam passing into the producer with the air; but this is rather an advantage than other-

wise as the steam is decomposed by the red-hot carbon and enriches the producer gas:

$$H_2O + C = 2H + CO;$$

$(2H + O = H_2O$: generates 58,060 calories.)

Gas Producers.—The gas producers are the furnaces in which the fuel is contained while the air is passed through it. The main objects to be accomplished are: (1) To pass the air uniformly

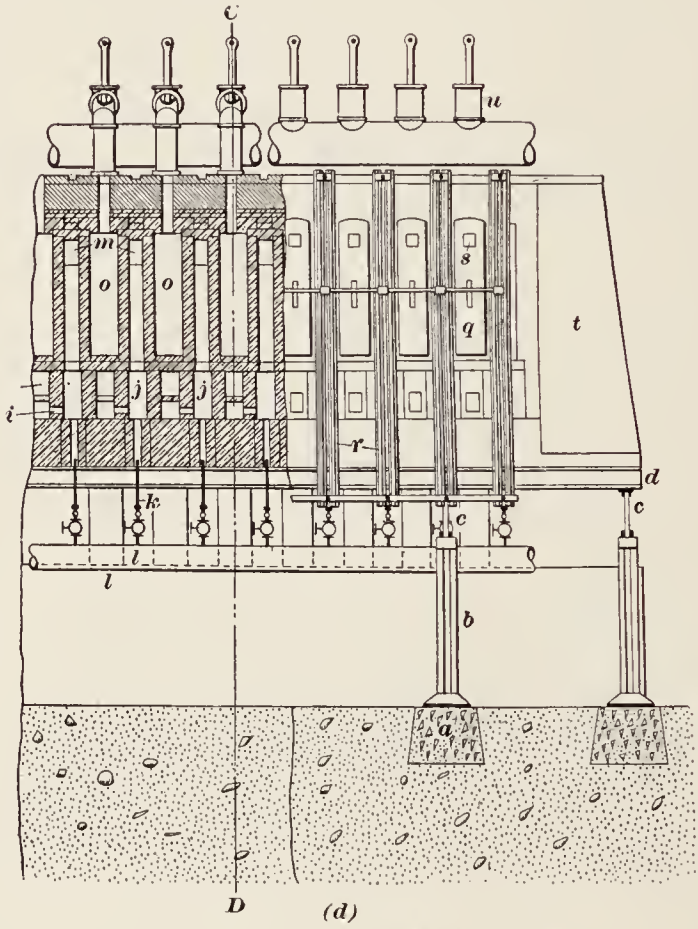


FIG. 361.—OTTO-HOFFMANN OVEN.

through the bed; (2) to remove ashes and charge fresh fuel without interrupting the production of gas; and (3) to preserve the deep bed of incandescent carbon, having level upper and lower surfaces. There are three horizontal zones in the gas producer: The first is the ash zone, which is deep in order that the air may be slightly preheated in passing through it and that any unburned carbon which gets into it may have a strong liability of being burned. Next above that is the CO_2 zone, in which the oxygen

and carbons are first combined; and above that the CO zone, in which the CO_2 is reduced by more carbon. The top of this zone should be at a dull-red heat.

There are many different forms of producer, which are extensively used for open-hearth work, but these may be divided into two general types: In the first or water-sealed type, the bottom of the producer dips into a pool of water and thus the tools may be introduced for the removal of the ashes at will. In this type there are sometimes steel arms extending into the bed of fuel, either from the top or from a central shaft, by the rotation of which the bed is poked, lumps and channels are broken up, etc. The second type has a mechanical grate, by which the ashes can be scraped down into the chamber underneath without interrupting the producer operation for the purpose.

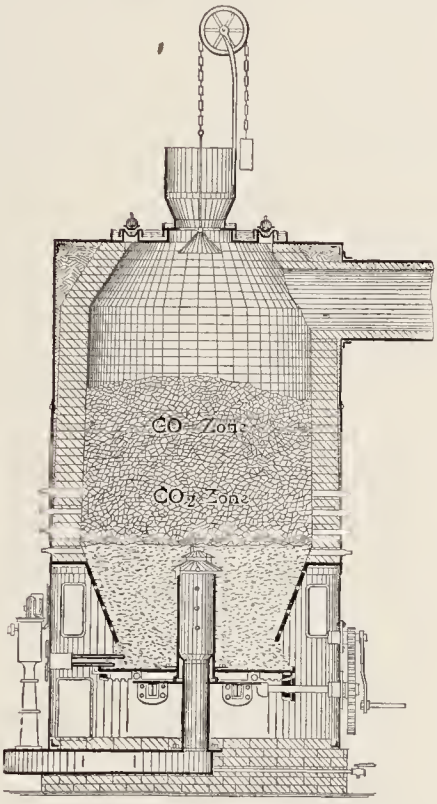


FIG. 362.—TAYLOR REVOLVING BOTTOM GAS PRODUCER.

Grate Area.—The total grate area of all the producers supplying gas to a furnace should be about 3.5 sq. ft. per ton of furnace capacity; some producer plants run even higher than this, and up to 6.25 sq. ft. Another method of figuring the grate area is that 1 sq. ft. should be supplied for every 7.5 to 12.5 lbs. of coal burned per hour, although with expert gas makers and good coal the combustion may be much greater than this, and higher values (to 22 lbs.) are claimed by the makers of the gas producers.

Volume and Calorific Power.—The volume of producer gas obtained from a ton of coal will be about 150,000 to 170,000 cu. ft., having a calorific power of 33 to 36 calories per cu. ft., or 130 to 145 B.t.u. per cu. ft.[1] These figures will, of course, depend upon the quality of the coal gasified, but the calorific power is no

1 For calculation of this relation see page 473.

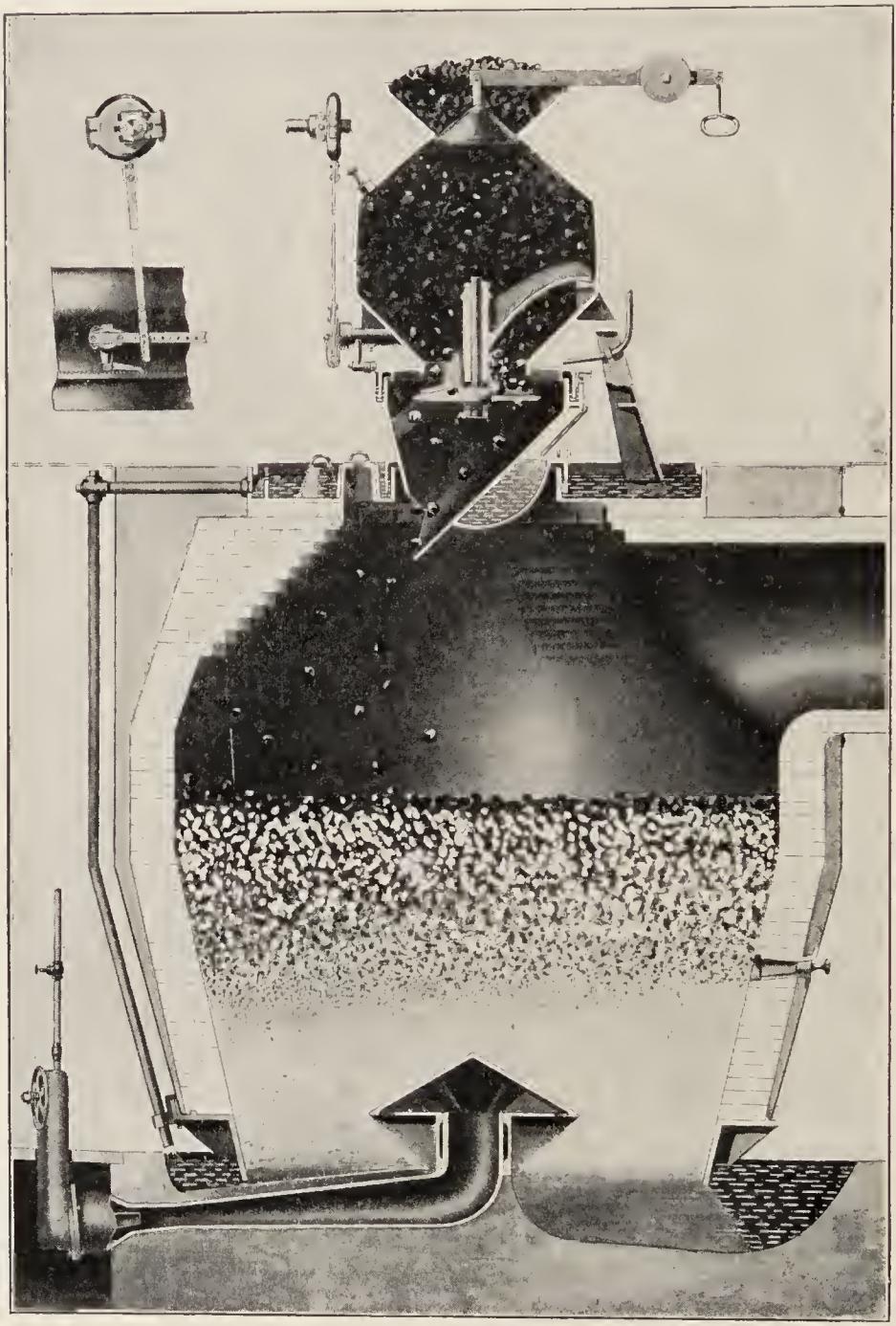


FIG. 363.—MORGAN WATER-SEALED GAS PRODUCER.

more important than the amount of heat that it will radiate, which depends upon the luminosity of the flame.

Luminosity.—The luminosity of flames depends upon the amount of hydrocarbons, and especially of heavy hydrocarbons,

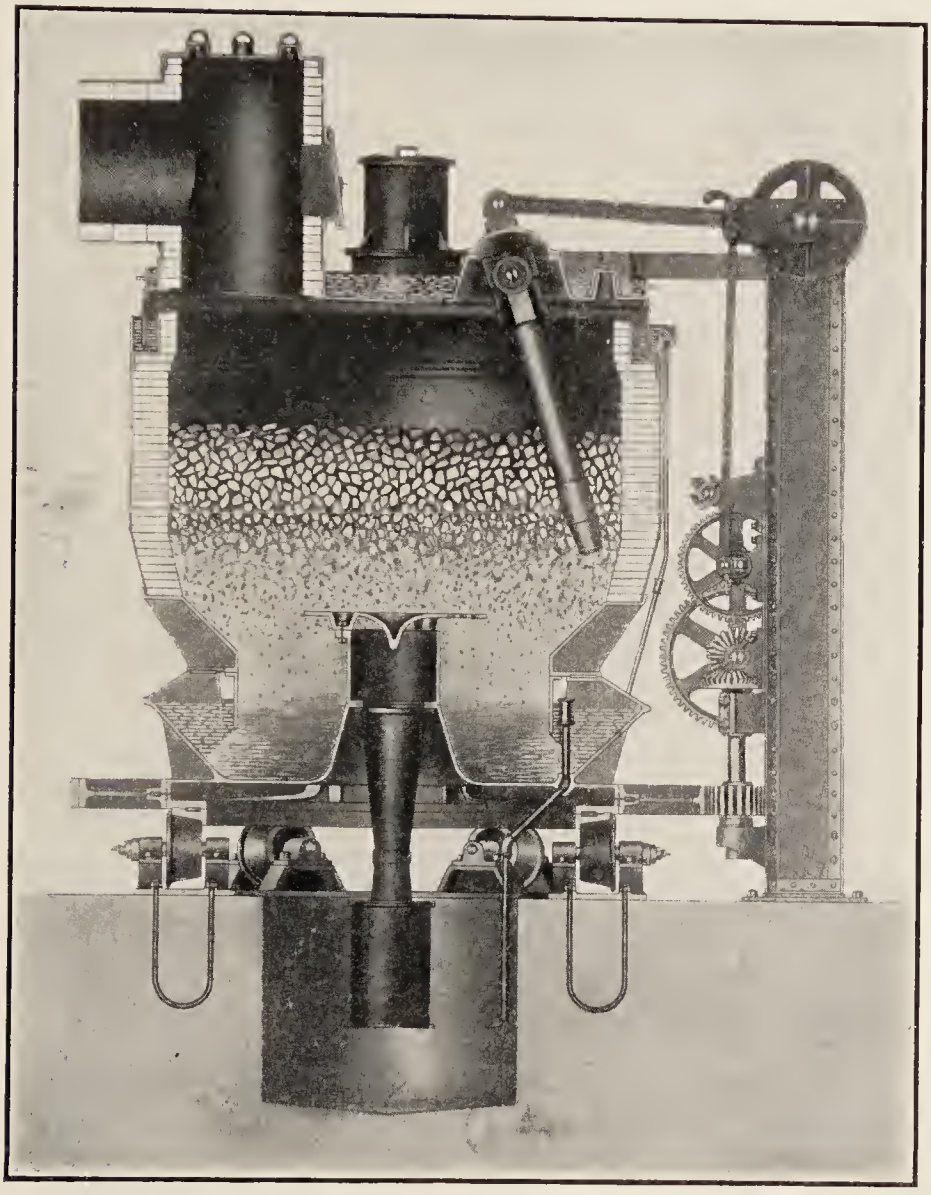


FIG. 364.—HUGHES MECHANICALLY POKED GAS PRODUCER.

burned to produce them. It is therefore necessary, if the producer gas is made from bituminous coal low in hydrocarbons or from coke or anthracite, to increase its illuminating power by spraying oil into it. The luminosity is produced by the deposition

of a myriad of tiny particles of carbon, which are heated to incandescence and then radiate energy in the form of light. It is probable that this action is produced by the relatively light hydrocarbons, such as methane (CH_4), breaking up first into ethylene (C_2H_4), and then into acetylene (C_2H_2), which deposits the carbon particles or soot. It is for this reason that the pure acetylene flame has such intense luminosity.

Gas Mains.—The gas mains leading from the producer plant to the open-hearth furnace should be lined with brick and be at

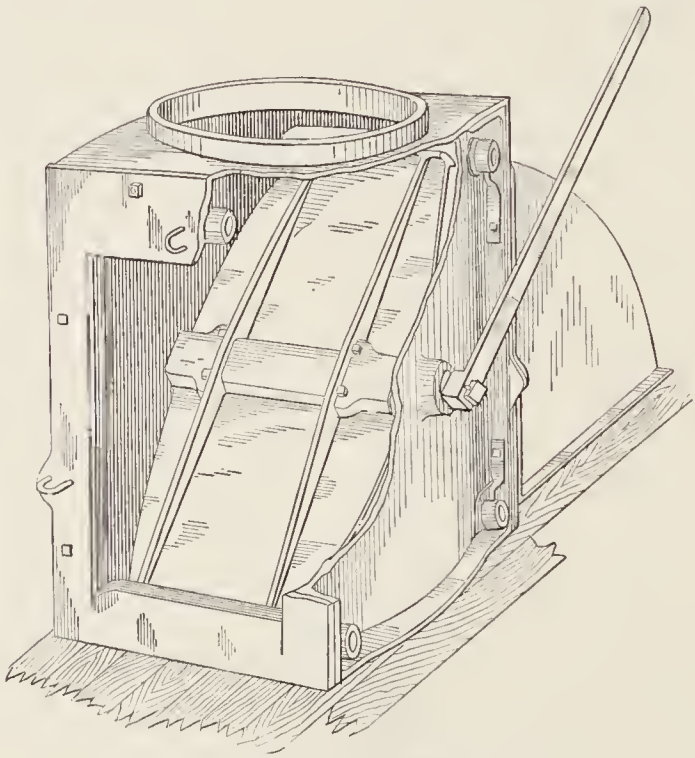


FIG. 365.—BUTTERFLY REVERSING VALVE.
(See also Fig. 32, page 171.)

least large enough for a man to pass through. Beyond this, a good rule is 1 sq. ft. of area of cross-section of gas main for every 8 sq. ft. of total combined area of gas-producer grates. The gas loses heat by radiation in the mains and deposits the tarry constituents, i.e., the nearly solid hydrocarbons, in both ways losing heating power.

Natural Gas.—In those districts, like Pittsburg, where natural gas occurs, it is a great boon to the open-hearth steel industry, because of its high calorific power and the cheapness with which

it may be obtained, and about 80 wrought-iron plants and 90 steel plants in America use it. It is drawn from the earth, and has a calorific power of 970 to 1010 B.t.u. per cu. ft. (equivalent

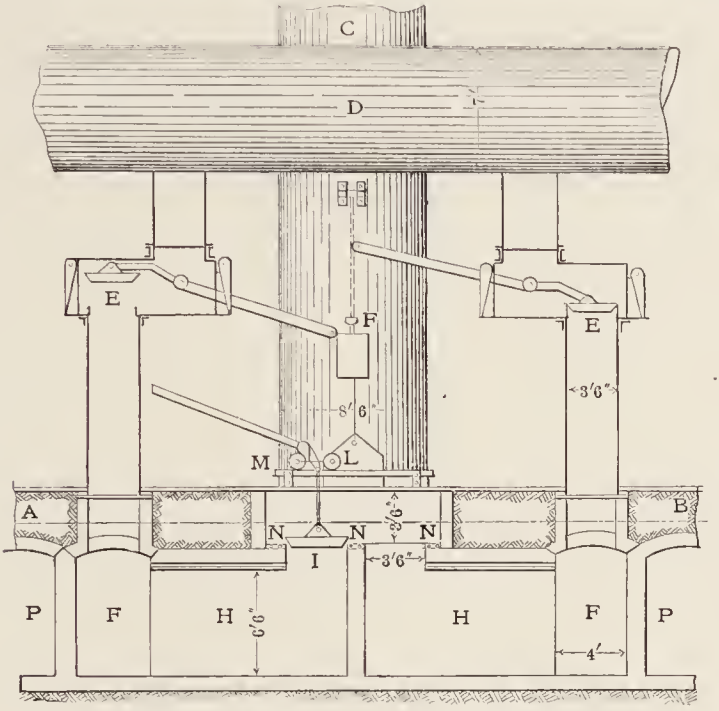


FIG. 366.—MUSHROOM REVERSING VALVE.

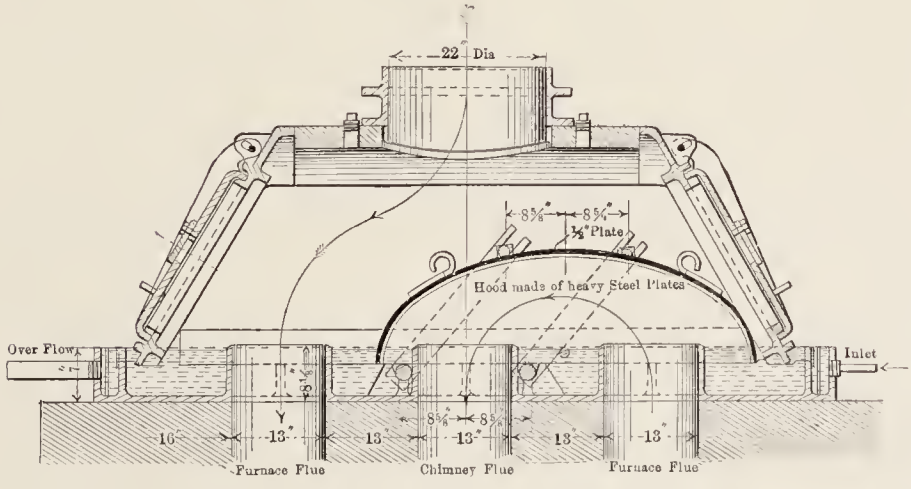


FIG. 367.—WATER-SEALED REVERSING VALVE.

to 225 to 250 calories per cu. ft. or 8600 to 9000 calories per cu. meter).[1] In the Pittsburg district the amount of natural gas

[1] The calcuation of this relation will be found on page 473.

used per ton of steel made ranges from 4000 to 11,000 cu. ft., averaging about 5500. This includes the gas used in the furnace and the small amount necessary for heating the ladles. The natural gas is usually introduced through two pipes at each end of the furnace, which are located close to the bottom of the gas-ports and deliver the fuel about 3 1/2 feet back from the hearth. The natural gas is therefore applied without any loss in gas mains, reversing valves, regenerators, etc., and is cheaper in labor on the furnace floor itself. The Pittsburg natural gas averages about 70 to 90 per cent. of methane (CH_4) or marsh gas, the remainder being hydrogen with a fraction of a per cent. of carbon dioxide and a very few per cent. of nitrogen.

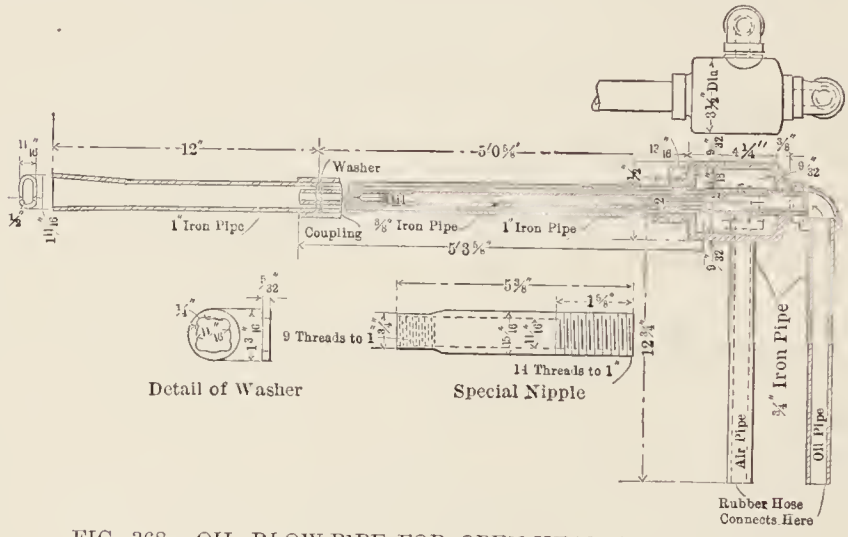


FIG. 368.—OIL BLOW-PIPE FOR OPEN-HEARTH FURNACE.

On account of its high calorific power, it is not necessary to preheat this gas, and this is the more fortunate, because the amount of hydrocarbon is so great that if the gas be passed through regenerative chambers, it decomposes and deposits soot on the checker-work. All the open-hearth furnaces in the Pittsburg district are so arranged that they can be put on producer gas in case it should become necessary, because the supply of natural gas has been decreasing for many years. In the early part of 1908, some furnace plants of a very important company in this district began the use of the manufactured gas, because of the increased cost of natural gas.

Oil.—On the continent of Europe, and in parts of the United States distant from the natural gas and bituminous coal regions,

many open-hearth furnaces are heated by petroleum. The United States has many deposits of fuel oil, besides which it is sometimes possible to obtain a refuse from the oil refineries which is excellent for this purpose. There are therefore many different grades employed, but they will usually average from 7.8 to 8.3 lbs. per gallon, with a calorific power of 14,000 to 17,000 B.t.u. per pound. H. H. Campbell[1] states that a rough comparison may be made by assuming that 50 gal. of oil will give the same amount of heat as about 1000 lbs. of soft coal, and he has had a valuable amount of experience with this kind of fuel. It would seem,

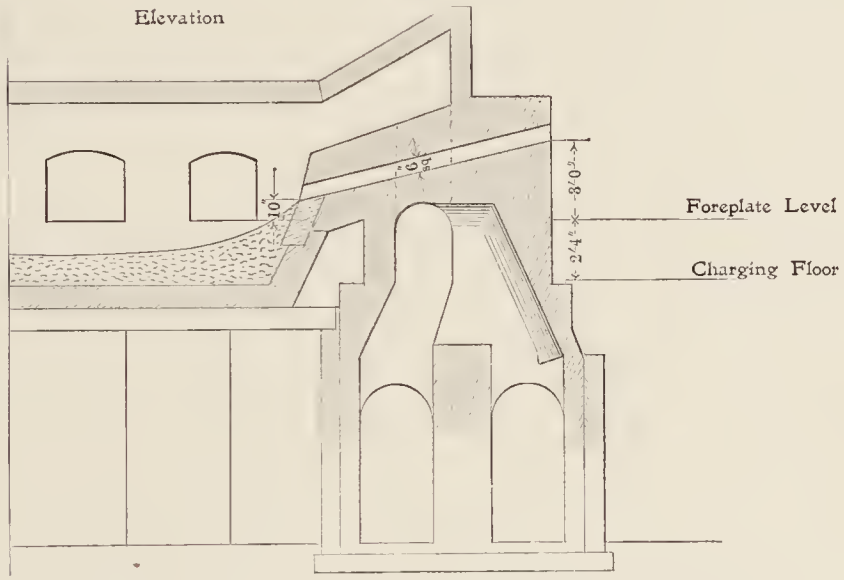


FIG. 369.—FURNACE ARRANGED TO USE OIL BLOW-PIPE.

however, as if this value for oil was somewhat high for safety in making calculations, and that a more conservative estimate would be to say that from 35 to 60 gal. of oil would be required per ton of steel treated in the open-hearth furnace. Eight furnaces using oil averaged 38 to 42 gal. per ton of steel made.

The crude petroleum is vaporized by atomizing it with a jet of steam or compressed air, and it is not common practice in the United States to pass this vapor through a regenerative chamber. The usual method of application is by a blow-pipe introduced through the brickwork at the end of the furnace, as shown in Fig. 369, and special forms of blow-pipe are now on the market for this purpose. It is necessary to pump the oil to the blow-pipe or

[1] See page 247 of No. 2 Old edition.

else to store it in an overhead tank, from which gravity will carry it, but the labor in connection with this is much less than the labor on gas producers. In the rare cases when the oil vapor is preheated, it must be introduced into the hot part of the regenerative chamber, because if it cools it condenses. Moreover, when introduced into a cold furnace or with a cold charge in the furnace, combustion will be retarded.

Whether oil is used or not will depend principally upon freight, because it may be transported much more cheaply than any other form of fuel. It gives a longer flame than either natural or producer gas, and one very great advantage of using it is a saving of the roof of the furnace; the oil flame may be directed so accurately by means of the blow-pipe that it does not impinge directly on the roof, and the brickwork therefore lasts very much longer. On the other hand, it spreads out horizontally and causes a greater wear on the front and back walls of the furnace. It gives a more uniform heat, a more oxidizing flame, and no danger of losses or difficulties, in case there is a leak in the walls between the gas and air regenerators, which is not an infrequent occurrence with gas.

Water-gas.—If steam be made to pass through a bed of red-hot carbon, the product is a gas containing slightly less than 50 per cent. each of hydrogen and carbon monoxide and having a high calorific power:

$$C + H_2O = CO + H_2 \text{ (absorbs 28,900 calories).}$$

The result of this reaction is a reduction of the temperature of the fuel bed, which is rapidly reduced until another reaction begins to take place:

$$C + 2H_2O = CO_2 + 4H \text{ (absorbs 18,920 calories).}$$

Therefore some means must be employed to raise the temperature at intervals, and this is ordinarily accomplished by interrupting the passage of steam and passing air through the fuel bed, which raises the temperature and at the same time forms producer gas which is used for other purposes. Usually, it is necessary to blow air through for 12 to 15 minutes, and then steam for 4 or 5 minutes. Consequently, the manufacture of water-gas is intermittent and the method is not very satisfactory for open-hearth work, although the gas is used to some extent on account of its high calorific power. This operation produces roughly 35,000 cu. ft. of water-gas and 80,000 cu. ft. of producer

gas per ton of coal. Water-gas has about 2600 cals. per cubic meter, or say, 290 to 300 B.t.u. per cubic foot.[1]

Dellwik-Fleischer System.—The Dellwik-Fleischer system is a modification of the ordinary water-gas system, in that the amount of air blown through for heating up the fuel is so very large that carbon dioxide is produced instead of carbon monoxide. This

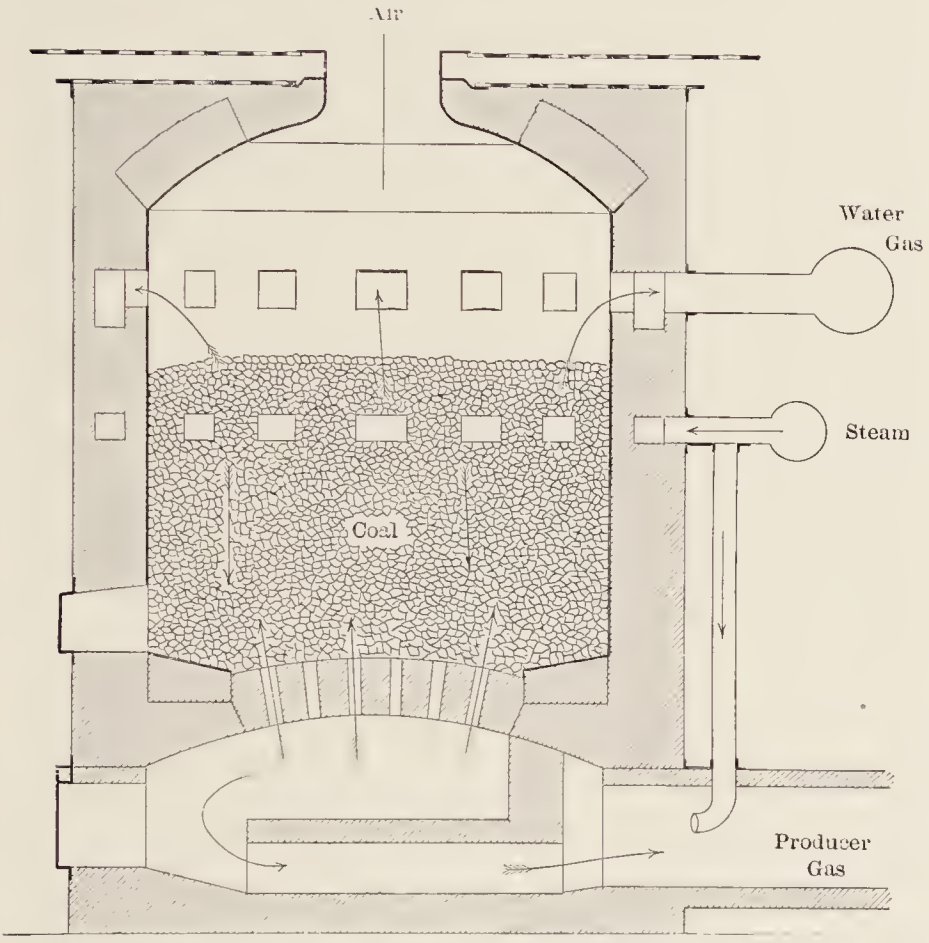


FIG. 370.—WATER-GAS PRODUCER.

gas is therefore altogether wasted, but the formation of carbon dioxide generates so much more heat that the blowing up does not take so long, and usually lasts from 1 1/2 to 2 minutes, after which water-gas is made for 8 to 12 minutes. In this way about 80 per cent. of the calorific value of the fuel is converted into

[1] One cubic meter = 35.3 cubic feet.
One calorie = 3.968 B. t. u.
One calorie per cubic meter = 8.9 B. t. u. per cubic foot.

water-gas, and several steel-works in Europe have adopted the method.

Mond Gas.—In the Mond process a mixture of water-gas and producer gas is made continuously. For every ton of fuel burned there is forced into the producer about 3 tons of air and 2.5 tons of steam, the latter being produced by absorbing the sensible heat of the gas in the boiler. It gives about 150,000 cu. ft. of gas per ton of fuel burned, containing about 25 per cent. of hydrogen, 12 1/2 per cent. of CO, 45 to 50 per cent. of nitrogen, and 12 1/2 per cent. of CO_2. This gives a slightly higher calorific power than ordinary producer gas, and is used in some steel-works.

XX

CHEMISTRY AND PHYSICS INTRODUCTORY TO METALLURGY

Chemical Changes.—If a piece of coal be burned, it ceases to exist as such. It disappears from sight, except for its slight residue of ash, and apparently has been wiped out of existence forever. Likewise, if a piece of steel be attacked by some acid, it disappears as such, and only a coloration of the acid gives evidence to the eye of the metal previously present. Lastly, if a piece of bright iron or steel be exposed to the weather, it is soon converted into reddish-brown rust, which bears but little resemblance to the original metal. In the first example the solid coal has been combined with oxygen of the air and converted to the form of an invisible gas; in the second case, the iron has been combined with the acid and water and converted into a liquid; in the third case the iron has been combined with oxygen and converted into a powder. In no case has there been any loss in total amounts or weights, but only a difference in composition or substance. These changes in composition are chemical changes.

Physical Changes.—Changes may occur in form or properties without any change in composition: For instance, water may be converted into ice by mere cooling, and no change in composition will take place. Or it may be converted into steam by heating and will still be composed of the same elemental constituents as when it was in the form of ice or water. Iron may be liquid or solid; it may be cold or hot; it may be magnetic or non-magnetic, and all without change in substance. These changes in properties are known as physical changes. They may consist of changes in form, strength, heat, light, magnetism, electricity—in fact, everything but composition.

Relation Between Chemical and Physical Changes.—Every chemical change produces one or more physical changes. Thus, chemical changes are always accompanied by a loss or gain of heat, and in the examples cited in paragraph 1, there were also observed changes in from, in color, etc. Conversely, we shall

see too that physical changes are often the cause of starting chemical changes: heat is necessary to start the chemical action of the burning of fuel; pressure produces the explosion of dynamite; electricity breaks up many chemical compounds; light produces the chemical changes that make the photograph.

Chemical Compounds and Mechanical Mixtures.—When coal is burned it is chemically united to the oxygen of the air, and the gas formed contains properties entirely different from anything belonging to either of the substances that compose it. Likewise when steel is dissolved in an acid, or is converted to rust. This is the essential characteristic of chemical action: that the substances acting upon each other lose their individual properties and produce a new substance with different properties. Not so when the substances are merely mixed together, no matter how intimate the mixture may be. If finely ground sulphur be mixed with finely ground iron no new properties are produced, but if the mixture be heated until a chemical action takes place and the two substances unite, a new compound is formed, with new and different properties. Moreover, once the chemical union has taken place the iron and sulphur cannot be separated except by chemical means, whereas the mixture of the two could be separated by mechanical means, such as blowing the sulphur away with a slow blast of air, or picking up the particles of iron with a magnet.

Chemical Affinity.—The power that causes substances to unite, and that holds them together afterward is known as "chemical affinity." Like gravity, magnetism and some other great forces, its nature is not understood but its influence is very evident. Some substances have seemingly no affinity for each other (for instance, mercury and iron will not form a compound), while others have tremendous affinity—such as sodium and oxygen, which cannot be brought into each others' presence without uniting violently and generating much heat. Some substances have almost universal affinities, like oxygen which unites with every other elemental substance known except one, while others are relatively inert and form few compounds.

Conditions under which Chemical Action will Occur.—To start chemical action it is sometimes only necessary to mix the substances, as, for instance, sodium and water; in other cases we must apply heat, or pressure, or electricity, etc., even though the substances have great affinity for each other and unite vigorously

after the action is once started. In other cases chemical action is very slow, no matter how started as, for instance, the rusting of iron, etc. As a general thing an increase in temperature increases all chemical affinites, up to a certain point, but it increases some faster than others.

The Elements.—In the universe there are millions of chemical compounds, and these are mixed together to produce animal and plant forms, the earth, sea, etc. All these compounds are different combinations of only about eighty elemental substances, which are known as "the elements." The compounds can all be separated into their component parts by chemical means (perhaps aided by electricity), but the elements have so far resisted every attempt to break them down into simpler substances, and they are therefore considered as the simple substances and the basis of all matter. These eighty elemental substances are therefore of great importance, but some much more so than others, for only eleven of them form the great bulk of the earth as we know it, and the remainder are less abundant. The crust of the earth is made up of the following elements:

Oxygen	47.29 per cent.
Silicon	27.21 per cent.
Aluminum	7.81 per cent.
Iron	5.46 per cent.
Calcium	3.77 per cent.
Magnesium	2.68 per cent.
Sodium	2.36 per cent.
Potassium	2.40 per cent.
All others	1.02 per cent.

The air is 77 per cent. nitrogen and 23 per cent. oxygen. Pure water is 89 per cent. oxygen and 11 per cent, hydrogen. Plant and animal forms are composed chiefly of combination of carbon, hydrogen, oxygen and nitrogen.

The air is the only one of the foregoing bodies in which the elements are not severally united in the form of compounds of a more or less complicated nature, and it is because the oxygen of the air is in the free, or elemental, state that it is capable of performing the chemical work of supporting life and burning fuels.

Summary.—We have now found that the whole universe, so far as we know it, is built up of only about eighty different simple substances, which we call elements, and which are sometimes mixed together and sometimes chemically united,

forming many millions of different combinations. We have also learned that a chemical compound has properties different from those of any of the substances composing it, and that the elements of the compound are held together by what is known as "chemical affinity." We have learned that chemical action does not always take place when two or more substances are mixed together, but we have often to start it by heat, electricity or some others means. Lastly we have learned that all chemical action is accompanied either by a production or consumption of heat.

Synthesis.—When two or more elements are chemically united to form a compound, or when two or more compounds are chemically united to form a further compound, the building-up process is called a "synthesis."

Analysis.—On the other hand, when a compound is separated into the elements which compose it, the breaking-down process is called a "decomposition."

Definition of Metallurgy.—Metallurgy is the art of extracting metals from their ores and adapting them to their intended service. As iron occurs in the earth combined with one or more other elements, the process of extracting it consists in decomposing the compounds and obtaining the metal from them. But this is not all of the metallurgy of iron for, after it is extracted, it must be adapted to the service for which it is intended, and for this purpose various other elements are combined with it in proportions depending upon the uses to which the metal is to be put. Even one part of some of the added elements in ten thousand parts of iron will make a great difference in its properties, so that these syntheses must be performed with great care. Then too the physical treatment which metals are given affects some of them greatly.

Qualitative and Quantitative Chemical Analysis.—Chemical analysis is important in metallurgy in another connection, because every substance put into the furnaces for smelting, and every substance produced must be carefully "analyzed" in order that we may know exactly what is in them and guide our operations accordingly. A "qualitative analysis" will show what elements are in any substance, while a "quantitative analysis" will show how much of each is present.

Oxygen

Occurrence.—Oxygen occurs free in the air; combined with hydrogen in water, and combined with silicon, with metals and with many other elements in the earth's crust. It is the most abundant element known to us.

Uses.—Oxygen reacts chemically with coal, coke, oil, gas and other fuels to produce the heat for our fires, among which we must include prominently the fires so necessary in metallurgy. A familiar, if somewhat special, reaction due to oxygen may bring this home to us. When breathed into our lungs oxygen in the air performs certain chemical reactions which produce the heat that keeps us alive, and which purify the blood.

Preparation.—Oxygen is very easily prepared in a concentrated form in a great variety of ways. If, by means of combined pressure and cold, air be converted into a liquid, its two components may be separated by centrifugal force, or else the nitrogen may be allowed to evaporate, leaving the liquid oxygen behind. No chemical processes are necessary for this separation because the elements are not combined. Where a compound exists, other means must be employed. For example, water may be decomposed into oxygen and hydrogen by an electric current, and from 100 parts by weight of water we can always obtain 89 parts of oxygen and 11 parts or hydrogen, no weight being lost in the change.

Chemical Action.—Oxygen is an odorless, colorless, tasteless gas. At the ordinary temperature it forms few chemical reactions, but, when heated, is one of the most active of the elements, vigorously attacking, for example, hydrogen and carbon, as well as their joint compounds in the form of gases, when once a chemical reaction is started with a match, electric spark or similar means. It also attacks almost all the metals at a red heat, and some of them at lower temperatures—iron for instance, which is coated with an "oxide" upon being heated about twice as hot as boiling water. All the simple compounds of the elements with oxygen go under the name of "oxides," and their formation is accompanied with the production of heat.

Phlogiston Theory.—Centuries ago it was observed that lead, when melted and exposed to the air, became an apparently new substance, and at the same time gained in weight. Starting with the same weight of lead and allowing the action to go on until

complete, always resulted in the same gain in weight. The ancients believed that this action was the transfer from the fire to the metal of a certain indefinable substance which they called "phlogiston." They learned that if the lead and "phlogiston" were later heated with charcoal, metallic lead was again produced, and they said that the "phlogiston" was driven out of it. We now know that it was oxygen from the air that attacked the lead when melted and formed "lead oxide," and that when the lead oxide was heated with charcoal (carbon) the charcoal robbed the lead of its oxygen and formed "carbonic oxide" leaving metallic lead again.

Oxidation and Reduction.—When oxygen attacks an element and forms an oxide the process is said to be an "oxidation," and when an oxide is deprived of its oxygen and reduced to a metal the process is said to be a "reduction." Iron is "reduced" from its ores, which are usually oxides. Oxidation and reduction are therefore opposite actions in chemistry, the first adding something to a substance and the second taking something away. At first the terms were used in connection with oxygen alone, but are now applied to adding or taking away anything. In metallurgy oxidation and reduction are all-important, for everything that is reduced goes with the metals, and everything that is oxidized passes away with the impurities. In the example cited where melted lead was oxidized, the oxide separated itself from the metal just as fast as formed, floating upon the top of it, and when the reduction with charcoal was effected, the lead separated itself from the mass and dropped down into the bottom of the furnace as fast as it was reduced. This latter was then a metallurgical operation.

Combustion.—Combustion is a form of oxidation, in which a "combustible" is chemically united with oxygen, and, as we know, this combustion, or burning, is our chief means of obtaining heat. When there is just the right amount of both oxygen and combustible to enter into combination, we have "perfect combustion," but if the compound is formed and there is either oxygen or combustible left over, we have "incomplete combustion." Incomplete combustion always means waste of heat. Thus, we know that too much air passed through a fire-bed will carry waste heat up the chimney, or if we have too little oxygen and carry a combustible gas up the chimney, or leave unburned fuel on the grate, we again waste heat.

Thermo-chemistry

Chemical Energy.—If two or more substances combine and produce heat, they have chemical energy, and they transform this chemical energy into heat energy, which can be transformed in turn into other forms and into work. Not all chemical actions produce heat, but some are accompanied by a consumption of heat, and therefore use up energy, or rather, they transform energy into chemical work. But the heat energy so transformed into chemical work is not lost, for we can get it back again by reversing the action. For instance, if lead oxide be reduced, a consumption of heat occurs, and the same amount of heat will be produced if we burn the lead and produce the oxide again. So it is in every case: The heat produced by the formation of a compound is the same in amount as the heat consumed when the compound is broken up, and the heat produced by any chemical reaction is the same in amount as that consumed when the action is reversed. The science that treats of the heat changes accompanying chemical changes is called "thermo-chemistry." As a general thing syntheses and oxidations are accompanied by a production of heat, while decompositions and reductions are accompanied by an absorption of heat. Thermo-chemistry is very important in metallurgy because metallurgy is chemistry carried on at high temperatures, and the metallurgist must know how much heat is required for all his reactions, and by what reactions he may obtain it.

Maximum Affinity.—If iron is heated in air the oxide of iron is formed, and if this be mixed with powdered aluminum and the action started with a fuse, the aluminum will rob the iron of its oxygen and unite with it instead. The reason for this is that aluminum has a greater affinity for oxygen than iron has. This process of selection is a common one in chemistry and any substance will decompose a compound provided it can form a new compound with greater chemical affinities. Likewise, if we have a limited amount of a substance in the presence of two others, it will combine with the one for which it has the greatest affinity. For example, if we have liquid iron and aluminum in the presence of oxygen, none of the iron will be oxidized until all the aluminum has been oxidized.

Net Heat of Chemical Reactions.—When iron oxide is formed, 195,600 units of heat are evolved; when aluminum oxide is formed

392,600 units of heat are evolved. Therefore, when aluminum decomposes iron oxide and forms aluminum oxide instead, the net heat effect of the reaction is to evolve (392,600–195,600=) 197,000 units of heat. But suppose a reaction occurs in which the decomposition brought about consumes more heat than the compound formed produces? For example, if iron oxide is attacked by carbon and deprived of its oxygen there will be a net loss of heat, instead of a gain, because carbonic oxide generates only 29,160 heat units in its formation, while 195,600 heat units are consumed in the decomposition of iron oxide. Such a reaction would not go on unless we constantly supplied heat to the bodies. This is important in metallurgy because it means that when we smelt iron oxide with coke (carbon) we cannot reduce the iron unless we continually heat the bodies. In the case where aluminum reduced the iron it was only necessary to start the reaction, but with carbon smelting it is not only necessary to start the action with heat, but also to continually supply the (195,600–29,160=) 166,440 units of heat that are absorbed.

Temperatures.—Temperature is the degree of heat. There are two scales by which it is commonly measured, known respectively as the Fahrenheit and the Centigrade scale. In both of these the freezing- and boiling-points of water are taken as the standards. In the Fahrenheit scale, 32° is the freezing-point of water, and 212° is the boiling-point. Each degree is therefore 1/180 of this interval. In the centigrade scale 0° is the freezing-point and 100° is the boiling-point of water. Each degree is therefore 1/100 of this interval. One degree Centigrade equals 1 4/5° Fahrenheit. A table of comparison is shown in Table XXXVIII, page 504.

Heat Units.—The amount of heat in a body is different from its temperature; it takes much more heat to raise a pound of water to 200° F. than it does to raise a pound of iron, and more to raise iron than copper, lead, or gold. There are two standards by which amounts of heat are measured: A British Thermal Unit (known as B. t. u.) is the amount of heat required to raise one pound of water one degree Fahrenheit; a caloric is the amount of heat required to raise one gram of water one degree Centigrade. In both cases the water must start at its maximum density, which is at 39.1° F. (=4° C.). One B. t. u. equals 252 calories.[1] In

[1] One pound avoirdupois=453.59 grams; one ounce avoirdupois=28.3495 grams.

this book I shall generally use calories, as that is the ordinary system in scientific work. One Calorie = 1,000 calories.

Summary.—We have now learned that iron and steel metallurgy is chemistry at high temperatures, and that when iron is reduced from its ores, we must decompose the ores, which consumes a great deal of heat. We have also learned how heat is obtained from chemical reactions, and chiefly from combustion. We have learned that oxygen forms oxides with many of the elements, and that some of the elements have a greater affinity for oxygen than others, so that they will keep, or even take, the oxygen away from them. Lastly we have learned that any reduced substances will join with the metal in our furnaces, and any oxidized ones will join with the impurities, and that the reduced substances will not ordinarily mix with the oxidized ones, except in minute quantities.

Chemical Equations.

Combining Weights.—When elements unite in compounds they always do so in certain definite proportions. Compounds of oxygen and iron contain oxygen in multiples of 16 and iron in multiples of 56 parts; those of oxygen and calcium contain oxygen in multiples of 16 and calcium in multiples of 40. In brief, iron enters compounds in multiples of 56, oxygen in multiples of 16, calcium in multiples of 40. Sulphur enters in multiples of 32, carbon in multiples of 12, etc. These characteristic combining weights are known as "atomic weights" for a reason that will be evident shortly. A list of about one-half of the known elements with their atomic weights is given in the table on the next page, those which are of the least importance in metallurgy of iron and steel being omitted, and those which are of greatest importance being printed in small capitals.

The Atomic Theory.—The atomic theory supposes that all of the elements are made up of a myriad of tiny particles called atoms. The atoms are the smallest particles of matter that can exist; too small to be even conceived of by the imagination, and yet all having a definite size and weight and incapable of being divided into finer particles. All the atoms in any one element are alike in composition, size, and weight, but differ in these three properties from the atoms of all of the other elements. When two or more elements combine chemically the atoms of one are

TABLE XXXVII

Aluminum	Al	27	Magnesium	Mg	24
Antimony	Sb	120	Manganese	Mn	55
Arsenic	As	75	Molybdenum	Mo	96
Barium	Ba	137.4	Nickel	Ni	59
Bismuth	Bi	208	Nitrogen	N	14
Boron	B	11	Oxygen	O	16
Calcium	Ca	40	Phosphorus	P	31
Carbon	C	12	Potassium	K	39
Chlorine	Cl	35.5	Silicon	Si	28.4
Chromium	Cr	52	Silver	Ag	108
Cobalt	Co	59	Sodium	Na	23
Copper	Cu	63.6	Sulphur	S	32
Fluorine	F	19	Tin	Sn	118.5
Gold	Au	197	Titanium	Ti	48
Hydrogen	H	1	Tungsten	Wo	184
Iodine	I	127	Vanadium	V	51
Iron	Fe	56	Zinc	Zn	65.4
Lead	Pb	207			

These combining weights are used in the laboratories of chemical analysis, in calculating furnace burdens and similar work. A list should be kept for convenient reference.

locked with bonds of chemical affinity to the atoms of the others, and thus the weight of each element entering the compound is in proportion to the number and weight of its atoms.

Chemical Symbols.—In writing the elements it is customary to represent each by one or two initial letters, instead of writing the name out in full. This is a sort of shorthand of chemistry. The representative letters are taken from the Latin name of the elements, and the same symbols are employed in every civilized country of the world. The symbol for iron is Fe, because the Latin name for iron is *ferrum*. That for aluminum is Al; for calcium, Ca; for carbon, C; for hydrogen, H; for magnesium, Mg; for manganese, Mn; for oxygen, O; for phosphorus, P; for silicon, Si; and for sulphur, S. These eleven symbols should be learned as they will be used frequently in the body of the work. Others are shown in Table XXXIII.

Multiple Proportions of Atomic Weights.—It has been found that some of the elements can combine in different numerical ratio in some compounds from that they do in others. For instance, one atom of carbon may combine with one atom of oxygen, and again one atom of carbon may combine with two atoms of oxygen. In the first compound there will be 12

weights of carbon and 16 of oxygen; in the second, 12 weights of carbon and 32 of oxygen. Likewise, one atom of iron may combine with one atom of oxygen, or two atoms of iron may combine with three atoms of oxygen. Each of these compounds will have different properties. It is possible to represent these compounds in a very simple way by using the symbols for the elements, for each symbol designates one atom of the element. To represent the first compound of carbon and oxygen we write their symbolic letters together—thus, CO. To represent the compound containing one atom of carbon and two of oxygen we write, COO or, CO_2. To represent the first iron oxide we write—FeO. To represent the second one, Fe_2O_3. Then the formulæ for these compounds tell us not only what elements make up the compound, but also how much of each is present. For example, in the first iron oxide we have 56 parts of iron and 16 parts of oxygen; in the second we have 112 parts of iron and 48 of oxygen.

Molecules.—When two or more atoms are held together by chemical affinity the particle formed is known as a molecule. The symbol, CO, represents a molecule of carbonic oxide; Fe_2O_3 represents a molecule of iron oxide.

Chemical Equations.—Chemical shorthand may be used to represent chemical reactions, and will indicate at a glance what is taking place. A synthesis will be shown as follows:

$$C + O = CO;$$

Carbon and oxygen produce carbonic oxide.

The decomposition of water would be written:

$$H_2O = 2H + O;$$

Water gives hydrogen and oxygen.

The reduction of iron oxide by carbon:

$$FeO + C = Fe + CO.$$

Iron oxide and carbon give iron and carbonic oxide.

The reduction of iron oxide by aluminum:

$$Fe_2O_3 + 2Al = 2Fe + Al_2O_3;$$

Iron oxide and aluminum give iron and aluminum oxide.

Indestructibility of Matter.—In the equations written above it will be noticed that there are always as many atoms of each element on the left-hand side of the equation mark as on the right. This is in accordance with the fundamental law of chemistry that matter can neither be destroyed nor created. If we combine carbon with oxygen the weight of carbonic oxide formed is exactly equal to the weight of carbon and oxygen together. Also, if we

decompose water the total weight of hydrogen and oxygen will be equal to the weight of water from which it came.

Hydrogen

Occurrence.—Hydrogen forms 11 per cent. of water, which is a compound of hydrogen and oxygen, whose molecules contain two atoms of hydrogen and one of oxygen, so that they have the formula, H_2O. Hydrogen also occurs in all living forms.

Properties.—Hydrogen is a colorless, tasteless, odorless gas, and the lightest substance known, so that it would be very useful for filling balloons except for its cost. It has a high chemical affinity for oxygen and a stream of it when ignited will burn readily in the air and produce water vapor with the evolution of 58,060 calories:

$$2H + O = H_2O (+ 58{,}062 \text{ cals.}).$$

It is therefore a good combustible, and an impure form of it is indeed one of our important fuel gases, going under the name of "water gas." It is also a good "reducing agent"; that is, it will reduce substances by taking their oxygen away.

Hydrocarbons.—Hydrogen has a strong affinity for carbon, and forms with it a long series of compounds known as "hydrocarbons," of which there are about two hundred different combinations. These form the basis of mineral oil, or petroleum, from which we get kerosene, gasoline, naphtha, benzene, lubricating oils, vaseline, paraffine, etc. The "light hydrocarbons" are found in kerosene, gasoline, etc., while the heavy hydrocarbons" are found in the less volatile oils. Some of the more important compounds are as follows: Methane, whose molecule has the formula, CH_4, is the chief constituent of natural gas; when it burns the following reaction takes place:

$$CH_4 + 4O = CO_2 + 2H_2O.$$

Ethylene, C_2H_4, is a heavier hydrocarbon than methane because its molecule contains more atoms of carbon, while acetylene, C_2H_2, is heavier still and is the most powerful illuminating gas known. Benzene, C_6H_6, has the same relation between the atoms of hydrogen and carbon as acetylene, but a different number of them in the molecule, so that it is an entirely different substance with different properties.

Thermo-chemistry of the Hydrocarbons.—When methane burns we get the following reaction:

$$CH_4 + 4O = 2H_2O + CO_2. \quad (+191{,}270 \text{ cals.})$$
$$-22{,}250 \text{ cals.} + 116{,}320 \text{ cals.} + 97{,}200 \text{ cals.}$$

If we put the heat of combination under each of the compounds then we can readily calculate the net heat produced or consumed by the reaction, because all the compounds on the left of the equation mark are decomposed and all those on the right are formed. Therefore the sum of the heats on the left is to be compared with the sum of the heats on the right. If the right-hand sum is greater, heat is produced; if the left-hand sum is greater, heat is destroyed. In the burning of methane 191,270 calories are produced and we therefore place (+191,270 cals.) at the end of the equation.

Let us now consider for comparison the reduction of tin oxide by carbonic oxide, as follows:

$$SnO_2 + CO = SnO + CO_2 \quad (-2{,}560 \text{ cals.})$$
$$-141{,}300 \text{ cals.} - 29{,}160 + 70{,}700 \text{ cals.} + 97{,}200 \text{ cals.}$$

In this case we find that the sum on the left is greater, and 2,560 calories are consumed. We therefore place (−2,560 cals.) next to the equation.

Preparation of Hydrogen.—The cheapest method of obtaining hydrogen is by decomposing water. This may be done as follows:

$$Na + H_2O = H + NaOH \quad (+33{,}700 \text{ cals.})$$
$$(\text{sodium}) - 69{,}000^1 + 102{,}700$$

We see that this is a heat-producing reaction. Another way:

$$C + H_2O = 2H + CO \quad (-28{,}900 \text{ cals.})$$
$$-58{,}060^1 \quad +29{,}160$$

We do this by passing water vapor over red-hot carbon, but the reaction consumes heat so we must frequently heat the carbon or the reaction will not go on.

Still another way is to pass an electric current through a body of water. Hydrogen gas appears at one electric connection and oxygen gas at the other. This process is known as the "electrolysis" of water, and it is an operation in "electro-chemistry." If it is carried out perfectly the amount of electric energy passed into the water will be equal to the amount of heat energy required for the decomposition—that is, 69,000[1] calories.

[1] The heat of formation of water is 69,000 cals. in liquid form and 58,060 in gaseous form. For other heats of reactions, see page 124, No. 53.

Summary.—Now we have learned that each element is constituted of infinitesimal particles called atoms which in any one element are all identical in weight and composition, and that when elements form compounds the atoms of one are joined to those of the other by bonds of chemical affinity. We have also learned that atoms of elements are represented by letter symbols, and that we can express reactions between them by putting the symbols together in molecules and then showing how they break up and change places to form other molecules, and that there are no atoms and no weight lost or gained in any of these changes, but there is a gain or loss in heat energy to correspond exactly with each loss or gain of chemical energy. And we have seen how the loss or gain of heat may be determined by reckoning the total heat of compounds decomposed as heat lost, and the total heat of compounds formed as heat produced. From this point we shall go on to consider the important elements more in detail as to their chemical behavior.

Elements, Compounds, and Radicals

Metallic and Non-metallic Elements.—All the metals are elements, but some of the elements are not metals; for instance, we know without being told that oxygen is not a metal. The distinction between metallic and non-metallic elements is not very clear. It once was considered that all elements which looked like metals should be classified as such; they were said to have "metallic luster." And all others were classified as non-metals. But this classification has been shown to be deceiving, and a chemical one has taken its place. Now all the elements that form "bases" are classified as metals, and all those that form "acids" are classified as non-metals.

Acids and Bases.—Acids have certain characteristic chemical properties and bases have certain other characteristic properties. Acids will destroy the characteristic properties of bases and neutralize them, and conversely, bases will neutralize acids. Acids and bases have strong affinity for each other and either one will attack the other if opportunity offers. That is why a basic slag will attack an acid furnace lining, or an acid slag will attack a basic lining. Metallurgical acids are "anhydrous" (water-free).

Salts.—When an acid and a base just neutralize each other they form what is known as a salt. Let us dissolve 36.5 grains of

hydrochloric acid, HCl, in water, and put a piece of paper soaked in litmus in it; the paper will at once turn a brilliant red. Now let us dissolve 40 grains of caustic soda, NaOH, in another vessel. Caustic soda is a strong base; if we put one end of our piece of red litmus paper in the solution it will turn blue. Now let us pour the acid solution into the basic solution, and we will get the following reaction:

$$\underset{36.5}{HCl} + \underset{40}{NaOH} = \underset{58.5}{NACl} + \underset{18}{H_2O}.$$

Now, 36.5 is the molecular weight of HCl (because one atom of hydrogen weighs 1, and one of chlorine weighs 35.5), and 40 is the molecular weight of NaOH (one atom of Na = 23; one of O = 16, and one of H = 1); therefore there must be as many molecules of HCl present as of NaOH, and a complete neutralization will occur. Moreover it will be seen that the total weight of atoms at the right of the equation mark is the same as that at the left. This neutralization forms "sodium chloride," which is our common table salt. The salt will be dissolved in the water used in the experiment. If now we put in this salt solution the piece of litmus paper, one end of which is red and the other blue, it will not change its colors at all.

Radicals.—Let us consider the neutralization of caustic soda by sulphuric acid, H_2SO_4:

$$\underset{80}{2NaOH} + \underset{98}{H_2SO_4} = \underset{142}{Na_2SO_4} + \underset{36}{2H_2O}.$$

In this reaction the SO_4 has changed places with the OH. When two or more atoms are joined together and travel around in company in this way, acting as if they were inseparable, they are called "radicals." In this reaction, the SO_4 is called an "acid radical," and the OH is called the "hydroxide radical." For the time being these radicals act as if they were elementary substances.

Valence.—Let us consider four compounds with hydrogen, as follows:

$$ClH \qquad OH_2 \qquad NH_3 \qquad CH_4$$

Hydrochloric acid, water, ammonia, methane.

One atom of hydrogen can hold one of chlorine, but it takes two to hold one atom of oxygen, three to hold one of nitrogen, and four to hold one of carbon. Conversely, one of chlorine can hold one of hydrogen, one of oxygen can hold two of hydrogen, one of

nitrogen, three, and one of carbon, four. This capacity for holding numbers of atoms is called "valence." In the compounds shown above, chlorine is uni-valent, oxygen is bi-valent, nitrogen, tri-valent, and carbon, quadri-valent. In each case hydrogen is uni-valent; indeed hydrogen is established as the standard of valency, with a holding power of one. We can determine the valence of other elements by learning how many atoms of hydrogen they will hold, or, if they do not form a compound with hydrogen, we can compare them with some other element that does. For example, calcium forms a very common oxide, CaO, known as lime. In lime calcium holds one atom of oxygen; but it takes two atoms of hydrogen to hold one atom of oxygen; therefore calcium is bi-valent.

Chemical Stability.—We have already seen enough compounds to know that the valence of several of the elements is not a constant quantity. For example, carbon and hydrogen atoms unite in nearly two hundred different combinations. Likewise, iron forms FeO and Fe_2O_3. In the first it has a valence of two; in the second, of three. But there is a difference in the stability of these compounds; the oxide, FeO, can only exist under strong reducing conditions, and will take on more oxygen with the least opportunity. Iron forms two sulphides, designated as FeS and FeS_2. In the second compound it has a valence of four, but this sulphide is not as strong a one as the other, and the second atom of sulphur may be driven off by heating it slightly: $FeS_2 = FeS + S$.

Ferrous and Ferric Compounds.—The oxide, FeO, is called "ferrous oxide"; while FeS is called "ferrous sulphide." The oxide, Fe_2O_3, is called "ferric oxide," while FeS_2 is called "ferric sulphide." Manganese forms two oxides: MnO is called "manganous oxide," and MnO_2 is called "manganic oxide." So with all compounds; that having the lower valence is given the suffix -ous, and that with the higher valence, -ic.

Mono-, Bi-, Tri-, etc.—FeS is also called "iron mono-sulphide," from the Latin, meaning one; FeS_2 is sometimes called "iron bi-sulphide." MnO is called "manganese monoxide," and MnO_2, "manganese bi-oxide" (di-oxide is sometimes used instead of bi-oxide). H_2O is "hydrogen monoxide"; H_2O_2 is "hydrogen di-oxide." Fe_2O_3 is called "iron sesqui-oxide," from the Latin meaning three halves.

Oxidizing Agents.—When oxygen is added to a compound

it is said to be oxidized. For example, FeO will be oxidized to Fe_2O_3 ($2\,FeO + O = Fe_2O_3$). Oxidation can only be produced by means of some "oxidizing agent." The commonest oxidizing agent in metallurgy is the oxygen of the air, and the next most important in iron and steel processes is Fe_2O_3, and slags very rich in Fe_2O_3:

$$3Si + 2Fe_2O_3 = 3SiO_2 + 4Fe$$
$$6P + 5Fe_2O_3 = 3P_2O_5 + 10Fe$$

Another important one is carbon di-oxide:

$$Fe + CO_2 = FeO + CO.$$

Reducing Agents.—When atoms are taken out of the molecule of a compound it is said to be reduced. Reduction can only go on in the presence of some "reducing agent." The commonest reducing agent in metallurgy is carbon in the form of coke, charcoal, etc.

$$SiO_2 + 2\,C = Si + 2\,CO.$$

Another one is carbon monoxide, and another is hydrogen:

$$Fe_2O_3 + CO = 2FeO + CO_2.$$

Manganese is also a reducing agent for iron:

$$FeO + Mn = Fe + MnO.$$

Chemical Reactions and Compounds

Organic and Inorganic Chemistry.—The chemistry of living organisms, such as plants, animals, etc., is a very complex subject, and need not be discussed here. Because carbon enters into all organisms we may describe organic chemistry as the chemistry of the carbon compounds. Inorganic chemistry is the chemistry of the metals and of compounds in which carbon enters in relatively small proportions. Inorganic chemistry is the only one that concerns metallurgists especially.

Wet and Dry Chemistry.—In the analytical laboratories they perform their chemical reactions by dissolving everything in water and so getting them in the liquid form, because solids do not unite with each other rapidly, and gases are not easily controlled. This branch of chemistry is known as "wet chemistry." In iron and steel metallurgy, however, we get everything in liquid form by melting it. This is known as "dry chemistry." The reactions that take place in dry chemistry are the same in

principle as those of wet chemistry. The chief difference is that we bring substances into the intimate contact necessary by fusion instead of by solution.

Carbon.—Carbon occurs in the earth in the crystallized form as graphite and as diamonds. Of these the diamond is the purer variety, but both may be considered as pure carbon in different forms. It occurs in naure in the impure form of coal, in quantities vastly greater and commercially of the highest importance. The element may be obtained in a massive, or uncrystallized, form by burning organic matter, such as wood, when a black residue of carbon (charcoal) will be left. The most abundant occurrence of carbon is, however, in combination with other elements in the various forms of living matter, and also in inorganic compounds with metals, known as carbonates, such as the carbonate of lime, $CaCO_3$, called limestone, or, when in the crystallized form, marble.

When bituminous coal is burned with the proper deficiency of air, a silvery-gray residue is left which is an impure form of carbon, called coke. Crystals of graphite often are present on the surface of coke. This coke is one of the most important of all metallurgical reducing agents, as well as fuels. Carbon also forms a number of hydro-carbons which are used in the form of gases as reducing agents and fuels, because both their carbon and hydrogen will unite with oxygen.

Carbon forms two oxides—CO and CO_2. The first combination is accompanied with the production of 29,160 calories, and the second, 97,200 calories. The formation of CO is not complete combustion, because it will itself be further oxidized: $CO + O = CO_2$, with the evolution of 68,040 calories. The heat of formation of $C + O$ together with that of $CO + O$ is just equal to that of the reaction:

$$C + 2O = CO_2 (+ 97{,}200 \text{ cals.});$$
$$29{,}160 + 68{,}040 = 97{,}200.$$

Carbon di-oxide, CO_2, is an acid radical and unites with many bases to form "carbonates," of which the commonest are those of calcium, $CaCO_3$, magnesium, $MgCO_3$, and sodium, Na_2CO_3. As CO_2 is very volatile, the carbonates may be decomposed by heat, which drives off the CO_2 as a gas:

$$Na_2CO_3 = Na_2O + CO_2.$$

Chemical Behavior of Iron.—Iron is attacked by many of

the wet acids—sulphuric, nitric, hydrochloric, acetic, etc. It is attacked by oxygen when heated, and even when cold provided the air is damp. At a red heat, iron decomposes water vapor ($2\,Fe+3\,H_2O=Fe_2O_3+6H$). It has a high affinity for oxygen, and also for small amounts of carbon, silicon, sulphur, phosphorus, and hydrogen. The last-named gas will penetrate solid iron very readily at a red heat and form a compound with it. Iron practically never occurs native on the earth's surface except combined with oxygen or some other elements.

Chemical Behavior of Silicon.—Silicon has a high affinity for oxygen, with which it forms a very common oxide, SiO_2, which is known as silica. This compound is decomposed with great difficulty; the following reaction takes place only when we get to the very high temperature in the hearth of the iron blast furnace:

$$SiO_2+2C=Si+2CO\,(-121{,}680\text{ cals.})$$
$$-180{,}000\qquad +2\times 29{,}160=58{,}320.$$

We must remember the difference between silicon and its oxide, silica. Silicon never occurs uncombined in the earth, but silica is the most abundant constituent known to us. Quartz is a crystallized form of pure silica, while flint, jasper, agate, etc., are uncrystallized forms. Opal is silica combined with water.

Silicates.—Silica is the great acid of dry chemistry, and when in the melted condition will neutralize every base with which it comes in contact, forming a series of salts known as "silicates." The great bulk of the earth's rocks are either pure silica or silicates of the different metals, and all metallurgical slags are silicates. The mono-silicate of iron has the formula Fe_2SiO_4. But it is more commonly written $(FeO)_2SiO_2$, which is the same as $Fe_2O_2SiO_2$. The series of commonest iron silicates are given below:

$FeO.SiO^2$	Sub-silicate.
$(FeO)_2SiO_2$	Mono-silicate.
$(FeO)_2(SiO_2)_3$	Sesqui-silicate.
$FeO(SiO_2)_2$	Bi-silicate.
$FeO(SiO_2)_3$	Tri-silicate.

With lime, CaO, and magnesia, MgO, a similar series is formed, but the silicates of alumina, Al_2O_3, are more complicated in composition. The different metallic silicates have the property of dissolving in each other when melted, and of dissolving the oxides

of metals, and various other oxidized substances, but not of dissolving metals or reduced substances.

Feldspar.—With potassium and aluminum silica forms a series of silicates known as the feldspars, which are common constituents of the earth's crust. The feldspars are chiefly important because when reduced to powdered form they become clay, which has the peculiar property of becoming plastic when moistened. The purer clays melt at a very high temperature and are therefore used as the bond to hold together the material for the linings of furnaces, but the clays that contain much potassium or sodium melt relatively easily, and are not so "refractory." Clays contain a certain amount of water of crystallization, that is, water chemically combined with the molecule of the silcates. If they are heated so hot that this water of crystallization is driven out of them, they will not again become plastic.

Chemical Behavior of Aluminum.—Aluminum has great affinity for oxygen and is therefore used, like silicon, for the purpose of de-oxidizing steel:

$$3FeO + 2Al = 3Fe + Al_2O_3.$$

Indeed aluminum retains its oxygen more tenaciously than silicon, and even the highest temperature of our fuel furnace does not effect its reduction. The oxide of aluminum, Al_2O_3, is called alumina, is a common constituent of rocks, and when nearly pure is used as an ore of the metal, its reduction being effected in electric furnaces. Alumina is very refractory, that is, it will stand a high temperature without melting, and is neutral in character, that is, it is attacked neither by acid nor basic slags. It is therefore used as a neutral lining for some furnaces.

Chemical Behavior of Manganese.—Manganese has a higher affinity for both oxygen and sulphur than iron has, and is therefore used as a de-oxidizer and de-sulphurizer of iron and steel. If sufficient manganese is present, and the metal bath kept liquid a sufficient time, neither oxygen nor sulphur will be found combined with iron:

$$FeO + Mn = MnO + Fe;$$
$$FeS + Mn = MnS + Fe.$$

Chemical Behavior bf Sulphur.—Sulphur is found in the earth native (that is, free from combination), especially in volcanic regions, and also combined with metals as sulphides. Iron bisulphide, called "iron pyrites," FeS_2, is very abundant and is the chief source of sulphuric acid manufacture, while the sulphides

of copper, lead, and zinc are the principal commercial ores of those metals. Iron sulphides are not used so much as ores on account of the expense of ridding the iron of sulphur, which is very harmful to it. Sulphur readily combines with oxygen at a slightly elevated temperature to form SO_2 and SO_3, and these combine with water to form sulphurous and sulphuric acids ($H_2O + SO_2 = H_2SO_3$; and $H_2O + SO_3 = H_2SO_4$). In wet chemistry sulphuric acid attacks metals to form sulphates:

$$2Fe + 3H_2SO_4 = 6H + Fe_2S_3O_{12} \text{ or } Fe_2(SO_4)_3.$$
$$Ca + H_2SO_4 = 2H + CaSO_4.$$

Phosphorus.—Phosphorus occurs in nature usually as metallic phosphates, and chiefly as phosphate of lime, $Ca_2(PO_4)_2$, a natural mineral to which the name of apatite is given. It is in this form that it ordinarily gets into the blast furnace with the iron ores which it accompanies in the earth. Phosphate is necessary to animal and vegetable life and a good part of bones and other hard parts of living organisms are composed of it. The phosphates that will dissolve easily are therefore valuable fertilizers. Consequently certain slags which are used to remove the phosphorus from steel can be sold for fertilizing purposes.

Phosphorus acts the part of an acid-forming element, and the phosphate radical will form salts with many metallic oxides, but especially with iron oxides, magnesium oxide and lime, for the latter of which it has great affinity. But it is a weaker acid than silica, and silica will drive the phosphate radical away from all the basic radicals until the silica has completely satisfied itself. For this reason phosphorus cannot be combined in slags unless there is a superfluity of bases present over the amount necessary to surfeit the silica. In our steel furnace slags this means usually as least 40 per cent. of lime plus magnesia plus iron oxide.

Calcium and Magnesium.—Calcium forms a very common oxide, CaO, known as lime, and magnesia forms a similar one, MgO, called magnesia. These occur in nature chiefly combined with carbonic acid to form carbonates; $CaCO_3$ is called limestone, and $MgCO_3$, magnesite. The two carbonates often occur combined together in a compound having the formula $(CaMg)CO_3$. This type of formula is used to indicate that the calcium and magnesium replace each other in the arbonate in almost any relative proportion. The natural rock, $(Ca.Mg)CO_3$, has the mineralogical name of "dolomite."

Limestone is used as a material to add to the charge of the iron blast furnace because the carbonic acid is driven off in the upper levels of the furnace as soon as it begins to become hot ($CaCO_3 + \text{heat} = CaO + CO_2$) and the lime so produced serves as a base in the blast-furnace slag. Burnt limestone, that is, limestone from which the carbonic acid has been driven off by heat, is also added to the slags made in some of the steel furnaces, in order to increase their basicity. Lime has the peculiarity of absorbing moisture from the air and forming a hydrate [$CaO + H_2O = Ca(OH)_2$]. This is known as "slacking," and it causes the lime to lose its coherence. For this reason furnace linings cannot be made of it.

Magnesia is made by burning magnesite ($MgCO_3 + \text{heat} = MgO + CO_2$), and this is much used for making the basic linings of furnaces. Burnt dolomite is used for patching basic furnace linings, but it is not as durable as magnesia for the original lining.

Chemical Solutions

Chemical Compounds, Mechanical Mixtures, and Chemical Solutions.—We have learned that the differences between mechanical mixtures and chemical compounds are: (1) The properties of compounds are different from those of its components; (2) the formation of a compound is attended with the production or absorption of heat; (3) the components of a compound are held together with bonds of chemical affinity, and (4) the components always form the compound in the same definite proportions. There is another class of combinations different from both compounds and mixtures, and known as solutions. These have some of the characteristics of compounds and also of mixtures. (1) The properties of a solution are different from those of its components, but not to as marked a degree as is the case with compounds; (2) its formation is attended with the production or consumption of heat; (3) the components of the solution are held together by bonds of chemical affinity, and can only be separated by chemical means, or by electricity, but (4) unlike compounds, and to a limited degree like mixtures, the the components of a solution may vary widely in proportions. In some cases the variation is infinite, as with melted gold and silver, which will dissolve in each other in any proportion; likewise, with melted copper and

silver. In other cases the limit of solubility is very narrow, as in the case of melted iron, which will dissolve only about 5 per cent. of carbon, while carbon will dissolve apparently only 1 per cent. or so of iron.

Just as some substances resist all our efforts to make them combine chemically, so others refuse to dissolve. For instance, several salts and liquids will not dissolve in water, the best solvent known, or rather, dissolve to such a slight degree that, for practical purposes, it may be neglected. The same is true of iron and mercury, melted lead, and zinc, etc.

Essence of Solubility.—Just what the nature of the state of solution is cannot be told at present, but the atoms, or molecules, of the dissolved substance, known as the "solute," seem to be held by the molecules of the solvent. One striking difference existing between a solution and a mixture is that the solute seems to occupy no space. If we mix with hot water one-quarter of its weight of table salt, the level of the water will rise in the containing vessel an amount equivalent to the bulk of the salt, but, as soon as the water dissolves the salt, it will fall back to its original volume. In short, we now have a quarter more weight of material in the same bulk, so that the specific weight of the mass increases 25 per cent. In several ways which we have not space here to discuss we can know of the presence of a greater number of molecules than ordinary in the same space when two or more substances are dissolved in each other; for instance, "osmotic pressure," surface tension. Metals dissolved in each other are heavier than the same bulk of any of the metals alone.

Precipitation.—If we dissolve 27 per cent. of table salt in hot water and then allow the water to cool, some of the salt will fall out of solution again and crystallize. This action is called "precipitation. It is one of the most important actions in chemistry. We may cause a precipitation by another means: If we have as much of any salt dissolved in water as it will take, and then add to the solution a more soluble one, the water will dissolve the new salt and precipitate the old one in corresponding amount. The same applies in metallic solutions: If we have 5 per cent. of carbon dissolved in iron and then add some metallic silicon, the iron will precipitate graphite in flakes of "kish," and dissolve silicon. The commonest method of precipitating elements in wet chemistry is by producing chemical change: Suppose we have some table salt (NaCl) dissolved in water and add just enough

silver nitrate ($AgNO_3$) to react with it; we form silver chloride which is insoluble, and which precipitates almost instantaneously:

$$NaCl + AgNO_3 = AgCl + NaNO_3.$$

This is only a partial precipitation, because sodium nitrate is still left in solution, but is often of great service.

Solubility and Temperature.—As a general thing the higher the temperature the greater amount of solute can be dissolved in any given solvent. This rule is not universal, but usually applies in practical metallurgical chemistry. Five per cent., or even more, carbon will dissolve in iron at a high temperature, but some of this precipitates as the metal cools near its solidification temperature.

Alloys.—Metallic alloys are dependent upon solution for their formation. Two metals which will not dissolve cannot be made to form alloys, and, in practice, all alloys are made by dissolving melted metals in each other. The only exception is certain alloys made by dissolving solid metals in each other under great pressure.

Nature of Slags.—Slags are molten solutions, and, as a general rule, they will dissolve all the oxidized substances with which they come in contact in the furnace (except such as are artificially kept too cold to be affected, such as the furnace walls) and will precipitate all the reduced substances. For example, metals will be precipitated as fast as reduced from their combinations in the ores: phosphorus, if oxidized by being combined with some base as a phosphate, will be dissolved, but, if silica takes the base away from it, the reduced phosphorus will be precipitated again.

Some Principles of Physics

Dalton and Gay Lussac Law.—Air, oxygen, nitrogen, hydrogen, and a few other gases, are called permanent gases, and all these expand and contract under change of temperature according to the same law, which is, that they expand or contract 1/273 of their volume at 0° C. for each 1° C. their temperature is raised or lowered, provided the pressure upon them remains constant. On the Fahrenheit scale, this coefficient is 1/493 instead of 1/273. Thus air under a given pressure will have twice the volume at 273° C. that it has at 1° C. This is most easily explained and remembered in the form that the volume of permanent gases is proportional to the "absolute temperature," whose zero is 273°

below freezing on the Centigrade scale, and 493° below freezing (i.e.) 461° below zero, on the Fahrenheit scale. This law is only approximately true for vapors and gases other than permanent gases, for example, steam, ammonia, etc.

Boyle's Law.—The volume of gases also increases or decreases in proportion to lessening or increasing the pressure. Ordinarily gases are under the atmospheric pressure, which is 15 pounds per square inch. If we increase the pressure upon them to 30 pounds their volume becomes one-half; if we increase it to 45 lb., it becomes one-third, etc., UA_2.

These laws are often consolidated into the statement that the product of the volume and pressure is proportional to the absolute temperature or $P+V=RT$ where R is a constant depending on the gas.

Specific Gravity.—The specific gravity of bodies is the relative weights of a unit volume. For example, a cubic inch of iron weighs nearly eight times as much as a cubic inch of ice, and a cubic inch of lead or platinum weighs more still. The specific gravity of solids and liquids are usually compared with water as a standard, and water at its temperature of maximum density—4° C. (39.2° F.)—is given an arbitrary value of 1. Gases are usually compared with air as a standard, and air at 0° C. (32° F.) and under a pressure of 760 millimeters of mercury (=practically 15 lb. per square inch) is given an arbitrary value of 1.

Heat.—The atoms and molecules of all bodies are never in a state of rest, even though the body itself appears to be quiet. It is this constant and violent motion of the molecules which we know under the name of heat. To raise the temperature of a substance increases the motion and vice versa. In the case of solids the vibration of each molecule is of course confined to a very small space indeed, but in the case of gases, the molecules travel until they strike against some other body with force enough to resist them, as, for instance, some other molecule, or the walls of the vessel in which they are contained, when they rebound with equal velocity in another direction. It is, in fact, the constant impact of molecules upon the walls of the containing vessel that causes gases to exert pressure. It also explains why gases expand when their temperature is raised, provided the pressure under which they are confined remains constant, because if their motion is more rapid they exert greater pressure against the containing walls.

Conservation of Energy.—The law of conservation of energy tells us that energy can be neither created nor destroyed. We can convert chemical energy into heat, or heat into motion, but we cannot get energy out of anything into which we do not put an equivalent amount in some form or another. We may waste energy, such as energy lost in heat from friction which is useless to us, but it does not cease to exist.

Physical Properties of Metals

Tensile Strength.—The tensile strength of a body is its resistance to being pulled asunder. It is usually measured in pounds per square inch; that is to say, a bar of wrought iron for example, with 1 sq. in. cross-sectional area[1] will support about 50,000 lb. weight.

Stress and Strain.—A stress is a force put upon a body, and a strain is the deformation of the body produced by a stress. For instance, if a bar of wrought iron 1 sq. in. in cross-sectional area and 2 in. long be made to support a weight of 10,000 lb., it will stretch about 0.0007 inch; the 10,000 weight is the stress, and the 0.0007 in. is the corresponding strain.

Elastic Limit.—In the case just mentioned, if the 10,000 weight be removed the strain will be removed. That is, the bar will return to its original length of 2 in. Now if the same bar be loaded with 20,000 lb. it will stretch 0.0014 in., and again this elongation will be lost when the weight is removed. If, however, we load the bar with 30,000, it will stretch a little more than 0.0021 in., and now it will not return to its original 2-in. length when the weight is removed, but will be permanently elongated. It has taken a "permanent set," as it is called. The "elastic limit" of a body is the force necessary to produce the first permanent set. It is usually measured in pounds per square inch. Another way of expressing the elastic limit is to say it is the force beyond which the strain is not proportional to the stress.

Modulus of Elasticity.—The modulus of elasticity tells of the rigidity or stiffness of a body, that is to say, its rate of yielding under any stress up to the elastic limit. The modulus of elasticity is obtained by dividing any stress (up to the elastic limit) by the strain produced per inch of length. For example, the wrought iron mentioned in the last paragraph stretched 0.0014

[1] Say a round bar about 1 1/8-in. diameter, or a square bar 1 in. on a side.

in. in a length of 2 in. = 0.0007 per inch of length, with a stress of 20,000 lb. per square inch; its modulus of elasticity will then be:

$$\frac{20{,}000}{0.0007} = 28{,}500{,}000.$$

Percentage Elongation.—After a bar under tensile stress has passed its elastic limit it begins to be permanently elongated in the direction of the pull. A soft metal, like copper or mild steel, will stretch out somewhat like molasses candy before finally breaking, and may be almost twice as long as it was originally. The increase in length, divided by the original length, is the percentage elongation. It is usually measured on a length of 2 in., or of 8 in.

Reduction of Area.—When a bar is elongated it of course shrinks in cross-section; finally, just before the bar breaks, it usually "necks down" on either side of the point of fracture. This type of fracture occurs with soft metals. The original area, minus the area of smallest cross-section after fracture is called the "reduction of area" and this divided by the original area is the "percentage reduction of area."

Ductility.—The percentage elongation and the percentage reduction of area are usually taken together as the measure of the ductility of a metal.

Compressive Strength.—The compressive strength of a body is its resistance to crushing. It also is usually measured in pounds per square inch.[1] The terms "stress and strain," "elastic limit," and "modulus of elasticity" all have the same meaning when referred to compressive as to tensile stresses.

Transverse Strength.—If a bar 1 in. square be supported on thin edges placed 12 in. apart its resistance to a force applied half way between the supports is called its "transverse strength." Here again we have the same terms, "stress and strain," etc.

Impact.—If a bar be supported on thin edges placed a certain distance apart and then a falling weight be allowed to strike upon it at a point midway between the supports, its resistance to this force will give an indication of its strength under impact, while the amount that it will bend before breaking will indicate its ductility under impact, or under "shock."

Shearing Strength.—The resistance of a body to being cut in

[1] In Great Britain they often use long tons (2,240 lb.) per square inch, instead of pounds, both for tensile and compressive stresses.

two by a pair of knife edges is called its shearing strength. Rivets are sometimes tested in this way, because they are subjected to this kind of stress in service.

Torsion.—The resistance of a bar to being twisted like an augur is called its torsional strength. The number of twists it will endure before breaking gives an indication of its ductility under this stress.

Repeated Stress.—If a certain kind of stress be applied to a body, then relieved, applied again, and so on alternately, this class of test is called "repeated stress." A metal will break under many applications of a repeated stress much less in amount than that required to break it if constantly applied. It is to be understood, however, that the interval between the applications of the stress must be very short so the metal will have no opportunity to rest between applications.

Alternate Stresses.—If we place a body first under tension, then under compression, and so on alternately, it produces what is known as "alternate stresses." It is like in nature to bending a wire back and forth, and metals will break under alternate stress even less than their elastic limits under either tension or compression alone.

Toughness.—The toughness of a metal is its resistance to breaking after its elastic limit is passed. It is the direct opposite of brittleness.

Brittleness.—The brittleness of a metal is the ease with which it breaks after its elastic limit is exceeded. A very brittle steel will have an elastic limit exactly equal to its ultimate tensile or compressive strength; that is to say, it will take no permanent elongation or reduction of area; its ductility will be zero. Some metals are more brittle under shock than under constantly applied stress, and *vice versa.*

Malleability.—Malleability is the quality of being deformed under a hammer. Gold is the most malleable of metals and can be hammered into sheets of extreme thinness without cracking.

Resilience.—Resilience is springiness. A very resilient metal, that is, one with a small modulus of elasticity, would be unsuitable for a bridge even though strong, because its vibration under a moving load would be so great.

Hardness.—The hardness of a metal is its resistance to being scratched, or to wearing away under friction. In steel metallurgy hardness is often used to mean brittleness, but this is no longer

advisable, because we are now making hard steels that are also tough.

Allotropy.—Allotropy is the capacity that certain elements have of changing their properties without changing their composition or purity. For example, we may have pure carbon in the form of diamond, graphite, or charcoal; we may have iron in a magnetic or non-magnetic condition; we may have sulphur in a brittle or in a pasty state, etc. What the nature of allotropy is we cannot at present tell. It may perhaps have to do with the relations of the different atoms in the molecules of the element. When elements form compounds the atoms of one are joined to the atoms of the others, and even when elements are in the pure state their atoms are often joined together to form molecules. Allotropy may be a difference in the number of atoms that are in each molecule, or perhaps in the form in which they are joined together. An allotropic change is always accompanied by a loss or gain of heat.

Crystallization.—The tendency of most elements and compounds to arrange themselves into regular forms called crystals is really a powerful force of nature, and one of the most wonderful and charming studies imaginable. The crystalline forms of each particular substance are usually the same, or very similar, but different from almost all other substances. Each crystal is built up of smaller crystals, and these in turn of still smaller ones. The tendency to produce a regular form is well illustrated in the case of alum: If a piece of an alum crystal be broken off and the main part be immersed in a saturated alum solution, the crystal will slowly repair itself and renew the lost part until it is again perfect. Moreover, if the alum solution is impure, the crystal will take to itself only the pure salt, and leave the impurity.

TABLE XXXIV.—COMPARISON OF DEGREES CENTIGRADE AND FAHRENHEIT

Below zero		Above zero		Above zero		Equivalents	
C.	F.	C.	F.	C.	F.	C.	F.
−200°	= −328°	+ 525°	= + 977°	+1,250°	= 2,282°	1°	= 1.8
150	= 238	550	= 1,022	1,275	= 2,327	2	= 3.6
100	= 148	575	= 1,067	1,300	= 2,372	3	= 5.4
50	= 58	600	= 1,112	1,325	= 2,417	4	= 7.2
		625	= 1,157	1,350	= 2,462	5	= 9.0
Above zero		650	= 1,202	1,375	= 2,507	6	= 10.8
		675	= 1,247	1,400	= 2,552	7	= 12.6
C.	F.						
+ 0°	= +32°	700	= 1,292	1,425	= 2,597	8	= 14.4
25	= 77	725	= 1,337	1,450	= 2,642	9	= 16.2
50	= 122	750	= 1,382	1,475	= 2,687	10	= 18.0
75	= 167	775	= 1,427	1,500	= 2,732	11	= 19.8
100	= 212	800	= 1,472	1,525	= 2,777	12	= 21.6
125	= 257	825	= 1,517	1,550	= 2,822	13	= 23.4
150	= 302	850	= 1,562	1,575	= 2,867	14	= 25.2
175	= 347	875	= 1,607	1,600	= 2,912	15	= 27.0
200	= 392	900	= 1,652	1,625	= 2,957	16	= 28.8
225	= 437	925	= 1,697	1,650	= 3,002	17	= 30.6
250	= 482	950	= 1,742	1,675	= 3,047	18	= 32.4
275	= 527	1,000	= 1,832	1,700	= 3,092	19	= 34.2
300	= 572	1,025	= 1,877	1,725	= 3,137	20	= 36.0
325	= 617	1,050	= 1,922	1,750	= 3,182	21	= 37.8
350	= 662	1,075	= 1,967	1,775	= 3,227	22	= 39.6
375	= 707	1,100	= 2,012	1,800	= 3,272	23	= 41.4
400	= 752	1,125	= 2,057	1,825	= 3,317	24	= 43.2
425	= 797	1,150	= 2,102	1,850	= 3,362	25	= 45.0
450	= 842	1,175	= 2,147	1,875	= 3,407		
475	= 887	1,200	= 2,192	1,900	= 3,452		
500	= 932	1,225	= 2,237	2,000	= 3,632		

APPENDIX A

Literature Referred to in the Text

General Text-books and Reference Books on the Metallurgy of Iron and Steel

1. H. M. Howe. "Iron, Steel, and Other Alloys," 1903. Published by Sauveur & Whiting, Boston, Mass. This book contains three chapters upon the "Manufacture of Iron and Steel" and ten chapters upon its constitution and properties, especially from the standpoint of metallography. Upon this latter subject it is without an equal and, like the same author's larger work, bids fair to remain the standard authority for many years to come.
2. H. H. Campbell. "The Manufacture and Properties of Iron and Steel." Fourth Edition. New York and London. 1907. This is a great reference book by one of the best of the practical American metallurgical engineers. It is the best American reference book upon the manufacture of iron and steel, but is not intended especially for beginners or those without technical education.
3. A. Ledebur. "Handbuch der Eisenhuettenkunde." Fifth Edition. 1906. Leipzig. This is an excellent reference book for those who read German, and contains a very complete account of the metallurgy of both iron and steel, and of their properties. There are also classified lists of the literature upon each of the branches of the subject.
4. Sir I. Lowthian Bell. "Principles of the Manufacture of Iron and Steel." London. 1884. This book well accomplishes its aim, namely, to elucidate the principles of iron and steel manufacture, and no man can be either so well informed or so ignorant as not to understand the metallurgy of these metals better after reading it.

5. H. P. Tiemann. "Iron and Steel. (A Pocket Encyclopedia)." New York and London. 1910. There is a wealth of general information in this book arranged for ready reference because in alphabetical order. It is in fact an encyclopedia of the iron and steel industry, with a sufficient explanation of all the terms and processes and products likely to be met with by those interested in the industry or trade.

6. Joseph W. Richards. "Metallurgical Calculations." Part I, Introduction, Chemical and Thermal Principles, Problems in Combustion. 1906. Part II, Iron and Steel. 1907. These problems not only teach how to calculate many very important things in connection with furnaces and their efficiency, but give a good insight into the principles of the processes themselves.

7. James M. Swank. "Directory to the Iron and Steel Works of the United States." Embracing the Blast Furnaces, Rolling Mills, Steel Works, Forges, and Bloomaries in Every State and Territory. Prepared and published by The American Iron and Steel Association. Philadelphia. The first edition of this book appeared in 1873, and the seventeenth edition in 1907. The data given are very complete and are classified for convenient reference.

8. James M. Swank. "History of the Manufacture of Iron in All Ages, and Particularly in the United States from 1585 to 1892." Philadelphia.

9. "Ryland's Colliery, Iron, Steel, Tin-plate, Engineering and Allied Trades' Directory (For Great Britain only) with Brands and Trade Marks." 1906. Published by Eagland & Co., Ltd., London.

Léon Gages. "Traité de Métallurgie du Fer." In two volumes. Paris. 1898. The first volume covers the manufacture of iron and steel, and the second, foundry, mechanical treatment and properties.

John Percy. "Metallurgy. Iron and Steel." London. 1864. This classical book is now chiefly valuable for historical reasons, where its usefulness is often unexpectedly advantageous, as, for example, in patent litigations, but at the time it was written it was a model for wealth of information (although badly arranged).

Hermann Wedding. "Ausfuehrliches Handbuch der Eisenhuettenkunde." Braunschweig. 1906. Four volumes. This is an edited translation of Percy's "Iron and Steel," brought up to date and greatly enlarged with especial reference to German practice, which is the second largest in the world.

Andrew Alexander Blair. "The Chemical Analysis of Iron." A complete Account of all the best known Methods for the Analysis of Iron, Steel, Pig Iron, Iron Ore, Limestone, Slag, Clay, Sand, Coal, Coke, and Furnace and Producer-Gases. Sixth edition. Philadelphia and London. 1906.

10. *The Journal of the Iron and Steel Institute.*—Published in London. Vol. i, 1869. This periodical appears twice a year and contains not only many original articles of great value, but also an almost complete collection of abstracts of the literature of iron and steel that is published anywhere, classified under headings for convenient reference. Anyone beginning research in any branch of iron and steel metallurgy should commence with this journal, as soon as the text-books have been consulted.

11. *Stahl und Eisen.*—Published in Dusseldorf. Vol. i, 1881. This is the best German periodical on iron and steel, and contains not only many valuable original articles and abstracts, but also translations. It is particularly useful in this latter connection, because of its translations of many articles from the Swedish.

12. *Revue de Metallurgie.* Published in Paris. Vol. i, 1904. This is a very valuable periodical for those who read French, not only for its original articles, but also for its abstracts. Upon the more scientific side of metallurgy, that is to say the properties and constitution of iron and steel, alloy steels, etc., it is without an equal.

13. *The Mineral Industry.*—Its statistics, technical and trade. Published in New York. Vol. i, 1892. This contains a review every year of the technology and trade of each of the metals listed alphabetically, as well as the statistics of production, price, etc. The articles usually include a review of the progress of the metallurgy during the year.

14. *The Iron Age.*—Published in New York. Vol. i, 1869. This is the oldest and largest of the American iron and steel technical magazines, and deals not only with the scientific and technical side of the subject, but also acts as a sort of a weekly newspaper upon the condition of the iron trade and recent happenings of interest.

15. *Transactions of the American Institute of Mining Engineers.*—Published in New York. Vol. i, 1871. The American Institute of Mining Engineers is the leading aggregation of both mining engineers and metallurgists in America. These transactions contain many original articles of value.

16. James M. Swank. *Annual Statistical Report of the Secretary of the American Iron and Steel Association,* containing detailed statistics of the American and foreign iron trade. Published in Philadelphia.

17. *Iron Trade Review.* Published in Cleveland, Ohio. Although this magazine aims to deal principally with iron trade conditions, it contains also a great many technical articles of importance.

18. *Metallurgie.* Published in Halle am See. Vol. i, 1904. This German magazine contains a great many original articles and abstracts. One should refer to Nos. 2, 3, and the list given below:

References on the Manufacture of Iron

20. Robert Forsythe. "The Blast Furnace and the Manufacture of Pig Iron." The best modern American book on this subject.

21. Sir I. Lowthian Bell. "Chemical Phenomena of Iron Smelting." London. The classical treatise on the chemistry of the blast furnace.

22. Thomas Turner. "The Metallurgy of Iron."[1] London. 1895.

23. A. de Vathaire. "Les Hautes Fourneaux." Paris.

24. H. Bauerman. "A Treatise on the Metallurgy of Iron."[1] London, 1868.

25. M. A. Pavlov. "Atlas of Plans for Blast Furnace Construction." Gekatermoslov (Russia), 1902. Although these

[1] Starred books refer to both pig iron and wrought iron.

drawings are lettered in Russian, one gets much valuable information from them even without being able to read the language.

26. Frederick Overman. "The Manufacture of Iron." [1] Philadelphia, 1850.
27. W. Truran. "The Iron Manufacture of Great Britain." [1] London, 1865. Revised by J. Arthur Phillips and W. H. Dorman.

General Reference Books on Steel

30. Henry M. Howe. "The Metallurgy of Steel." Vol. i, 1890. New York. This is the recognized standard authority on the metallurgy of the Bessemer and crucible steel processes, and upon the properties of steel as far as they were known and understood at the time when this book was written. It will long remain a classic. There have been many editions of different dates, but no change in text since 1890.
31. F. W. Harbord. "The Metallurgy of Steel." 1905. London. With a Section on Mechanical Treatment by J. W. Hall. Next to No. 30, this is the most complete and thorough book on steel ever written in English. The section on mechanical treatment is the best extant.
34. H. Noble. "Fabrication de l'Acier." Paris, 1905. As its name indicates, this book deals chiefly with the manufacture of steel, the section on properties being very small.

References on the Bessemer Process

See Nos. 2, 3, 4, 30, 31, and the following list:

50. Richard Akerman. "The Bessemer Process as Conducted in Sweden." Trans. American Institute of Mining Engineers. Vol. xxii, 1893, pages 277 et seq.
51. Henry M. Howe. "Notes on the Bessemer Process." *Journal*, Iron and Steel Institute, No. 11, 1890, pages 100 et seq.
52. Bradley Stoughton. "The Development of the Bessemer Process for Small Charges." Trans. American Institute of Mining Engineers. Vol. xxxiii, 1903, pages 846 et seq.

53. Friedrich C. G. Müller. *Untersuchungen über dèn deutschen Bessemerprocess.* Zeitschrift des Vereines deutscher Ingenieure. Vol. xxii, 1878, pages 384–404 and 454–470. This is one of the most comprehensive studies of the metallurgy of the Bessemer process in any language.

54. Hermann Wedding. "The Basic Bessemer, or Thomas Process." Translated into English by William B Phillips and Ernst Prochaska. New York, 1891. This the the most complete account of the basic Bessemer process.

References on the Open-Hearth Process

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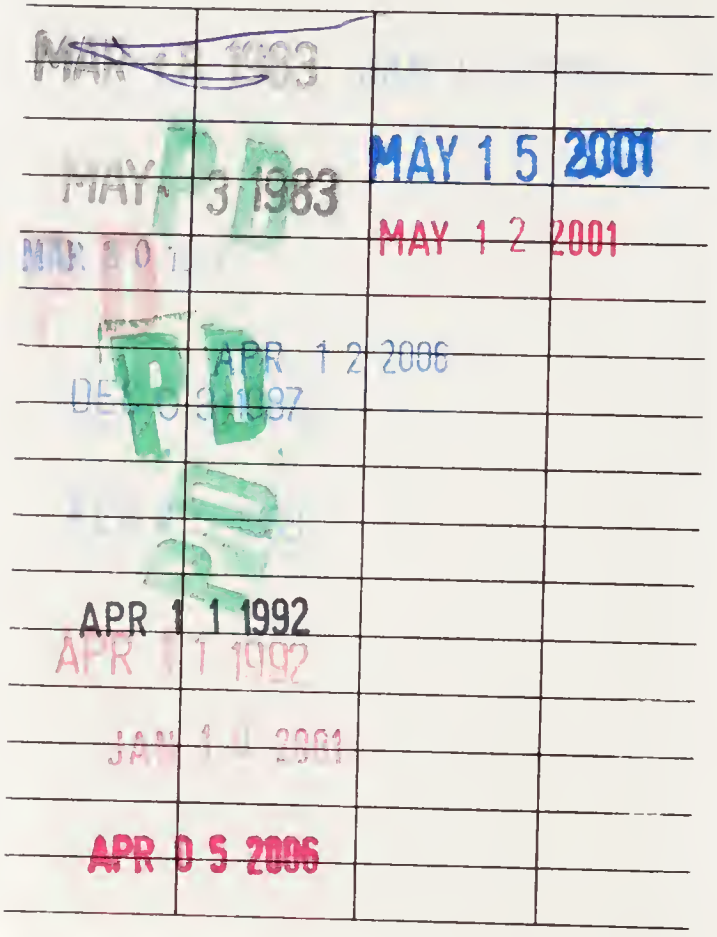

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